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THESIS

J2125

UTILIZATION OF A KALMAN OBSERVER WITH LARGE SPACE STRUCTURES

by

Bruce M. Jackson

December 1988

Thesis Advisor Jeff B. Burl

Approved for public release; distribution is unlimited.

T241978

REPORT DOCUMENTATION PAGE

eport Security Classification Unclassified		1b Restrictive Markings	
ecurity Classification Authority		3 Distribution Availability of Report	
Declassification Downgrading Schedule		Approved for public release; distribution is unlimited.	
rforming Organization Report Number(s)		5 Monitoring Organization Report Number(s)	
ame of Performing Organization val Postgraduate School	6b Office Symbol *(if applicable)* 33	7a Name of Monitoring Organization Naval Postgraduate School	
ddress *(city, state, and ZIP code)* nterey, CA 93943-5000		7b Address *(city, state, and ZIP code)* Monterey, CA 93943-5000	
ame of Funding Sponsoring Organization	8b Office Symbol *(if applicable)*	9 Procurement Instrument Identification Number	
ddress *(city, state, and ZIP code)*		10 Source of Funding Numbers	
		Program Element No	Project No / Task No / Work Unit Accession No

Title *(include security classification)* UTILIZATION OF A KALMAN OBSERVER WITH LARGE SPACE STRUCTURES

Personal Author(s) Bruce M. Jackson

Type of Report	13b Time Covered	14 Date of Report *(year, month, day)*	15 Page Count
ster's Thesis	From To	December 1988	85

Supplementary Notation The views expressed in this thesis are those of the author and do not reflect the official policy or po-on of the Department of Defense or the U.S. Government.

Cosati Codes			18 Subject Terms *(continue on reverse if necessary and identify by block number)*
ld	Group	Subgroup	Kalman Observer, large space structures.

Abstract *(continue on reverse if necessary and identify by block number)*

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A straightforward application of the Kalman Filter will be examined utilizing a steady state Kalman gain matrix. The bserver performance will be examined in both matched filter/plant and reduced order filter configurations.

Distribution Availability of Abstract unclassified unlimited ☐ same as report ☐ DTIC users	21 Abstract Security Classification Unclassified	
a Name of Responsible Individual ff B. Burl	22b Telephone *(include Area code)* (408) 646-2390	22c Office Symbol 62BL

D FORM 1473,84 MAR 83 APR edition may be used until exhausted
All other editions are obsolete

security classification of this page

Unclassified

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Utilization of a Kalman Observer with Large Space Structures

by

Bruce M. Jackson
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1976

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
December 1988

ABSTRACT

Control of the motions and vibrations of large space structures require the knowledge of state values that may not be available due either to inability to measure the states or, the high cost of the sensors to measure the required states. One solution is the use of an observer to estimate the states from limited sensor input.

The physical characteristics of large space structures and the enviroment they operate in will cause large amounts of noise in the measurements. The obvious observer for such an enviroment is the Kalman Filter which is specifically designed to produce optimal estimates in a noisy enviroment.

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ACKNOWLEDGEMENTS

I would like to express my appreciation to the McDonnel Douglas Astronautics Company of Huntington Beach, California, for allowing the use of their dynamic model of a preliminary space station configuration. Also, I would like to thank Major William J. Preston, USMC for allowing the use of the mathematical model for the station dynamics which makes up the majority of Chapter II of this paper as well as portions of his simulation program. Finally, I would like to thank Professor J. B. Burl for his assistance and most of all his patience in the completion of this work.

This paper is dedicated to Christina Marie Jackson (USNA '10).

I. INTRODUCTION

A. BACKGROUND

The advent of large space structures poses a number of problems for the control engineer. Previously, the objects put into space could be treated as rigid bodies so that a single three axis sensor package could be used to tell the motion of all components. The large space structures will not be rigid, instead they will have considerable flexibility and multiple modes of vibration [Ref. 1: p. 51]

Control of the structure's attitude and vibrations requires knowing the motions of the components. One approach would be to heavily instrument the space structure, but weight and cost make this approach impractical. An alternative is to use a limited number of sensors to measure only certain states and to deduce the other required states by use of an observer algorithm.

This thesis will address the production of estimates of the states needed for control of the structure. The model used will be a early design study by McDonnell Douglas Astronautics for a dual keel space station. The techniques and problems of observation for this model are generic to all large space structures.

B. PROBLEM STATEMENT

Design of an observer for estimating the states of a large space structure breaks down into several steps. First, a matematical model is developed for the system behavior over time. Modal analysis is used to form a system composed of decoupled second order differential equations. The use of decoupled equations allows a reduced order model to be generated by truncating the number of modal equations. A reduced order model will have all of the same mathematical qualities (and problems) but reduces the amount of time and computer resources required to do simulation.

Second, the observer is designed. The observer is designed to obtain a minimum variance estimate of the desired state values from the measurements.

Third, the observer is simulated to verify performance. Simulation runs of both a matched observer/plant system and a reduced order observer are employed. That is, the system is run where the observer is used to estimate all of the plant states and run where there are more plant states than the observer estimates.

Fourth, results are analysed and conclusions drawn based on these results. Reccomendations for further areas of research are suggested based on the results and conclusions.

C. ORGANIZATION

The model of the space station is developed in Chapter II. The modal model was developed using modal analysis and discretized to form the discrete-time state equations. The data for this model was from an early design study by McDonnell Douglas Astronautics Company for a dual-keel space station. The observer and its equations are developed in Chapter III. Chapter IV is the simulation runs of the observer versus the plant. Chapter V presents conculsions and recommendations for further research.

II. MATHEMATICAL MODEL

A. INTRODUCTION

Prior to the proposed space station almost all of the objects put into space could be treated as simple rigid bodies for the purpose of mathematical modelling of their motions. The design constraints imposed by the high cost of lifting mass to orbit dictates a light, open structure with considerable flexing. Large space structures such as the space station, therefore, cannot be treated as rigid bodies. The structure is in fact lightly damped with multiple natural frequencies. The result is a structure that will vibrate for considerable periods of time whenever external forces are applied.

The space station structure can be modeled as an n-DOF (degree of freedom) system consisting of n masses, springs, and dashpots [Ref. 2: p. 173-176]. This straight forward modelling of the coupled masses produces a system of unworkable complexity. As a result, the system will be modelled in terms of the structures natural modes of vibration. The resulting system, while still complex, is at least workable.

The model will be developed in two steps. The first will be to generate the continous-time model of the natural modes. The second will yield the discrete-time model, developed from the first model, for use in the simulation.

B. MODAL MODEL

The space station structure can be modeled as a system of discrete masses coupled by springs and dashpots. The major mechanism of damping in the structure is structural damping, the internal dissipation of energy within the members, as the structure vibrates. Structural damping can be shown to be equivalent to viscous damping and this equivalency is used in the model [Ref. 2: p. 72-73].

The energy dissipated by structural damping is:

$$Wd = \alpha X^2 \tag{1}$$

Wd = energy dissipated by structural damping

α = constant (force/displacement)

X = displacement

The energy dissipated by viscous damping is:

$$Wv = \pi c \omega X^2 \tag{2}$$

We can equate the two

$$\pi C_{eq}\omega \mathbf{X}^2 = \alpha \mathbf{X}^2 \tag{3}$$

yielding an equivalent viscous damping coefficient:

$$C_{eq} = \frac{\alpha}{\pi\omega} \tag{4}$$

The second order differential equation for a single viscously damped mass is:

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{5}$$

Substituting C_{eq} for c

$$m\ddot{x} + \frac{\alpha}{\pi\omega}\dot{x} + kx = F(t) \tag{6}$$

For multiple mass systems C_{eq} becomes $\frac{d}{\omega_f}\mathbf{K}$ where ω_f is the natural frequency of vibration.

The displacement of masses can be represented by the second order matrix differential equation [Ref. 3: p. 3-9],

$$\mathbf{M}\ddot{q}(t) + \frac{d}{\omega_f}\mathbf{K}\dot{q}(t) + \mathbf{K}q(t) = \mathbf{F}(t) \tag{7}$$

q = coordinate vector

$\mathbf{M}$ = system mass matrix (diagonal)

$\frac{d}{\omega_f}\mathbf{K}$ = equivalent damping

d = damping coefficient

ω_f = frequency of oscilation of the system

$\mathbf{K}$ = symmetric system stiffness matrix

$\mathbf{F}(t)$ = system forcing function

The above equation represents a system of second order differential equations coupled through the stiffness matrix. Decoupling can be done by expressing q in terms of natural modes of vibration. The process is called modal analysis. The independent differential equations can then be treated individually. The modal equations are derived below.

First, the undamped, homogeneous form of Eq. (7)

$$\mathbf{M}\ddot{q}(t) + \mathbf{K}q(t) = 0 \tag{8}$$

is solved. Let

$$q(t) = Ax \sin(\omega t + \Theta) \tag{9}$$

$$\dot{q}(t) = Ax\omega \cos(\omega t + \Theta) \tag{10}$$

$$\ddot{q}(t) = -Ax\omega^2 \sin(\omega t + \Theta) \tag{11}$$

substituting Eq. (9) and Eq. (10) into Eq. (11)

$$[-\omega^2\mathbf{M} + \mathbf{K}]\mathbf{A}x \sin(\omega t + \Theta) = 0 \tag{12}$$

This equation has a non-trivial solution for all time if and only if:

$$[\mathbf{K} - \omega^2\mathbf{M}]x = 0 \tag{13}$$

Equation (12) has n combinations of x (natural mode shapes) and ω (natural frequencies) as solutions. These can be grouped into matrices:

$$\mathbf{X} = [x_1 x_2 ... x_n]^T \tag{14}$$

$$\Omega^2 = diag[\omega_{o1}^2 \omega_{o2}^2 ... \omega_{on}^2] \tag{15}$$

which satisfy the equation:

$$\mathbf{KX} = \Omega^2\mathbf{MX} \tag{16}$$

Several useful relations can be derived from Eq. (16). Premultiplying Eq. (16) by $\mathbf{X}^T$,

$$\mathbf{X}^T\mathbf{KX} = \Omega^2\mathbf{X}^T\mathbf{MX} \tag{17}$$

The eigenvectors can be normalized

$$\mathbf{X}^T\mathbf{MX} = \mathbf{I} \tag{18}$$

which yields

$$\mathbf{X}^T\mathbf{KX} = \Omega^2 \tag{19}$$

The equations of motion can be uncoupled through the linear transformation of the coordinate system

$$q(t) = \sum_{i=1}^{n} x_i \eta_i(t) = \mathbf{X}\eta(t) \tag{20}$$

$\mathbf{X}$ = modal matrix

n = maximum number of degrees of freedom

$\eta(t)$ = transformed coordinate vector

Application of the transformation to the system Eq. (7) yields

$$\mathbf{X}^T\mathbf{M}\mathbf{X}\ddot{\eta}(t) + \frac{d}{\omega_f}\mathbf{X}^T\mathbf{K}\mathbf{X}\dot{\eta}(t) + \mathbf{X}^T\mathbf{K}\mathbf{X}\eta(t) = \mathbf{X}^T\mathbf{F}(t) \tag{21}$$

Using Eq.(18) and Eq. (19)

$$\mathbf{X}^T\mathbf{M}\mathbf{X}\ddot{\eta}(t) = \mathbf{I}\ddot{\eta}(t) = \ddot{\eta} \tag{22}$$

$$\frac{d}{\omega_f}\mathbf{X}^T\mathbf{K}\mathbf{X}\dot{\eta}(t) = \frac{d}{\omega_f}\Omega^2\dot{\eta}(t) = d\Omega\dot{\eta} \tag{23}$$

$$\mathbf{X}^T\mathbf{K}\mathbf{X}\eta(t) = \Omega^2\eta \tag{24}$$

therefore

$$\ddot{\eta} + d\Omega\dot{\eta} + \Omega^2\eta = \mathbf{X}^T\mathbf{F} \tag{25}$$

Equation (25) is the modal model of uncoupled second order differential equations. The motion of the structure can be found from the modal amplitudes, $\eta(t)$, using Eq. (20).

C. DISCRETE-TIME MODEL

The discrete-time state space model is found by solving the continuous-time equations. The *ith* equation of motion is

$$\ddot{\eta}_i(t) + d\omega_{oi}\dot{\eta}_i(t) + \omega_{oi}^2\eta(t) = \mathbf{X}_i^T\mathbf{F}(t) \tag{26}$$

$\mathbf{X}_i^T$ = transpose of the ith mode shape vector

$\mathbf{F}(t)$ = torquing force applied at a point

The homogeneous solution ($\mathbf{F}(t) = 0$) for Eq. (26) is [Ref. 4: p. 475-476]

$$\eta_i(t) = C_1 e^{-\gamma t}\cos(\omega_d t) + C_2 e^{-\gamma t}\sin(\omega_d t) \tag{27}$$

where

$$\gamma = \frac{d\omega_{oi}}{2} \tag{28}$$

$$\omega_d = \sqrt{\omega_{oi}^2 - \gamma^2} \tag{29}$$

The constants in Eq. (27) can be found by taking the derivative

$$\dot{\eta}(t) = (C_2\omega_d - C_1\gamma)e^{-\gamma t}\cos(\omega_d t) - (C_1\omega_d - C_2\gamma)e^{-\gamma t}\sin(\omega_d t) \tag{30}$$

and evaluating at $t = 0$

$$\eta(0) = C_1 \tag{31}$$

$$\dot{\eta}(0) = C_2\omega_d - C_1\gamma \tag{32}$$

Solving for C_1 and C_2

$$C_1 = \eta(0) \tag{33}$$

$$C_2 = \frac{\dot{\eta}(0)}{\omega_d} + \frac{\eta(0)\gamma}{\omega_d} \tag{34}$$

In matrix form

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{\gamma}{\omega_d} & \frac{1}{\omega_d} \end{bmatrix} \begin{bmatrix} \eta(0) \\ \dot{\eta}(0) \end{bmatrix} \tag{35}$$

Rewriting Eq. (27) and Eq. (30) in matrix form

$$\begin{bmatrix} \eta(t) \\ \dot{\eta}(t) \end{bmatrix} = \begin{bmatrix} e^{-\gamma t}\cos(\omega_d t) & e^{-\gamma t}\sin(\omega_d t) \\ e^{-\gamma t}[\gamma\cos(\omega_d t) + \omega_d\sin(\omega_d t)] & e^{-\gamma t}[\omega_d\cos(\omega_d t) - \gamma\sin(\omega_d t)] \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \tag{36}$$

Substituting Eq. (35) into Eq. (36), the solution can be written in terms of the initial conditions

$$\begin{bmatrix} \eta(t) \\ \dot{\eta}(t) \end{bmatrix} = \begin{bmatrix} e^{-\gamma t}[\cos(\omega_d t) + \frac{\gamma}{\omega_d}\sin(\omega_d t)] & \frac{1}{\omega_d} e^{-\gamma t}\sin(\omega_d t) \\ -\frac{\omega_o}{\omega_d} d^{-\gamma t}\sin(\omega_d t) & e^{-\gamma t}[\cos(\omega_d t) - \frac{\gamma}{\omega_d}\sin(\omega_d t)] \end{bmatrix} \begin{bmatrix} \eta(0) \\ \dot{\eta}(0) \end{bmatrix} \quad (37)$$

Letting

$$\mathbf{X}_i(t) = \begin{bmatrix} \eta_i(t) \\ \dot{\eta}_i(t) \end{bmatrix} \quad (38)$$

and

$$\mathbf{A}_i = \begin{bmatrix} e_{-\gamma t}[\cos(\omega_d t) + \frac{\gamma}{\omega_d}\sin(\omega_d t)] & \frac{1}{\omega_d} e^{-\gamma t}\sin(\omega d t) \\ -\frac{\omega_o}{\omega_d} e^{-\gamma t}\sin(\omega_d t) & e^{-\gamma t}[\cos(\omega_d t) - \frac{\gamma}{\omega_d}\sin(\omega_d t)] \end{bmatrix} \quad (39)$$

the solution can be written as

$$\mathbf{X}_i(t) = \mathbf{A}_i(t)\mathbf{X}_i(0) \quad (40)$$

where $\mathbf{A}_i$ is the state transition matrix of the *ith* mode. The non-homogeneous solution is

$$\mathbf{X}_i(t) = \mathbf{A}_i(t)\mathbf{X}_i(0) + \mathbf{B}_i x_i^T \mathbf{F}(0) \quad (41)$$

where the discrete-time input matrix, for constant $\mathbf{F}$, is given by

$$\mathbf{B}_i = \int_0^t \mathbf{B}_i(\tau)\Gamma\partial\tau \quad (42)$$

and $\Gamma = [0\ 1]^T$ is the input matrix for the continuous-time system, and T is the sampling time. Solving Eq. (42) yields

$$\mathbf{B}_i = \begin{bmatrix} \frac{1}{\omega_o^2}[1 - e^{-\gamma t}\cos(\omega_d t) - \frac{\gamma}{\omega_d} e^{-\gamma t}\sin(\omega_d t)] \\ \frac{1}{\omega_d} e^{-\gamma t}\sin(\omega_d t) \end{bmatrix} \quad (43)$$

The discrete-time state equation for the ith equation of motion can be written as

$$\mathbf{X}_i(kT + 1) = \mathbf{A}_i(T)\mathbf{X}_i(kT) + \mathbf{B}_i(T)x_i^T\mathbf{F}(kT) \quad (44)$$

where $\mathbf{A}_i$ and $\mathbf{B}_i$ are evaluated at $t = T$. Here,

$\mathbf{X}_i$ = vector of the ith modal amplitude and the ith modal velocity

$\mathbf{A}_i$ = ith state transition matrix

$\mathbf{B}_i$ = ith input vector

x_i^T = transpose of the ith mode shape vector

$\mathbf{F}$ = distrubuted force on the plant

T = sampling time

k = time index

Equation (44) can be expanded to include the disturbance input, $w(kT)$:

$$\mathbf{X}_i(kT+1) = \mathbf{A}_i(T)\mathbf{X}_i(kT) + \mathbf{B}_i(T)x_i^T[\mathbf{F}(kT) + w(kT)] \tag{45}$$

Equation (45) is the discrete-time mathematical model describing the motion of the structure in terms of its natural modes of vibration.

III. THE OBSERVER

A. INTRODUCTION

The observer design will be required to estimate the modal states in a noisy enviroment. Kalman filtering is the most widely used technique for accomplishing the production of state estimates in a noisy enviroment [Ref. 5: p.159]. The steady state Kalman filter was selected to minimize the computations during the actual plant observer operation. Use of a steady-state gain matrix for the observer allows the matrix to be computed separately from the operational observer, reducing the computer power required for the observer and allowing the algorithm to operate more rapidly.

B. KALMAN FILTER EQUATIONS

The discrete Kalman filter provides state estimates for the following dynamic sytem [Ref. 5: p. 159-162],

$$\mathbf{X}(k+1) = \mathbf{A}\mathbf{X}(k) + \mathbf{B}\mathbf{U}(k) + \mathbf{B}\mathbf{n}\mathbf{W}(k) \tag{46}$$

$$\mathbf{Y}(k+1) = \mathbf{C}\mathbf{X}(k+1) + \mathbf{V}(k+1) \tag{47}$$

$\mathbf{X}$ = n x 1 state vector

$\mathbf{U}$ = P x 1 control vector

$\mathbf{W}$ = r x 1 plant noise vector

$\mathbf{Y}$ = m x 1 measurement vector

$\mathbf{V}$ = m x 1 measurement noise vector

$\mathbf{A}$ = n x n state transition matrix

$\mathbf{B}$ = n x p control input matrix

$\mathbf{Bn}$ = n x r plant noise input matrix

$\mathbf{C}$ = m x n measurement matrix

The plant noise vector $\mathbf{W}(k)$ is gaussian white noise with

$$\mathbf{E}\{\mathbf{W}(k)\} = \mathbf{0} \tag{48}$$

$$\mathbf{E}\{\mathbf{W}(k)\mathbf{W}^T(k)\} = \mathbf{Q} \tag{49}$$

for all $k = 0,1,2,\ldots$, and $\mathbf{Q}$ is a positive semi-definite r x r matrix. $\mathbf{V}(k)$ is gaussian white noise with

$$\mathbf{E}\{\mathbf{V}(k)\} = \mathbf{0} \tag{50}$$

$$\mathbf{E}\{\mathbf{V}(k)\mathbf{V}^T(k)\} = \mathbf{R} \tag{51}$$

for all $k = 0,1,2,\ldots$, and $\mathbf{R}$ is a positive definite m x m matrix. The two random processes $\mathbf{W}(k)$ and $\mathbf{V}(k)$ are assumed to be independent, so that

$$\mathbf{E}\{\mathbf{V}(j)\mathbf{W}(k)\} = \mathbf{0} \tag{52}$$

for all $j = 1,2,\ldots$, and $k = 0,1,2,\ldots$ The intial state $\mathbf{X}(0)$ is assumed to be a gaussian random vector with

$$\mathbf{E}\{\mathbf{X}(0)\} = \mathbf{0} \tag{53}$$

It is assumed that $\mathbf{X}(0)$ is independent of $\mathbf{W}(k)$ and $\mathbf{V}(k)$.

The optimal estimate of $\mathbf{X}(k+1)$ is denoted $\hat{\mathbf{X}}(k+1 \mid k+1)$. The Kalman filter is designed to minimize

$$\mathbf{J} = \mathbf{E}\{[\mathbf{X}(k+1) - \hat{\mathbf{X}}(k+1 \mid k+1)]^T[\mathbf{X}(k+1) - \hat{\mathbf{X}}(k+1 \mid k+1)]\} \tag{54}$$

The recursive realtions for generating $\hat{\mathbf{X}}(k+1 \mid k+1)$ are

$$\hat{\mathbf{X}}(k+1 \mid k) = \mathbf{A}\hat{\mathbf{X}}(k \mid k) + \mathbf{B}\mathbf{U}(k) \tag{55}$$

$$\hat{\mathbf{X}}(k+1 \mid k+1) = \hat{\mathbf{X}}(k+1 \mid k) + \mathbf{G}(k+1)[\mathbf{Y}(k+1) - \mathbf{C}\hat{\mathbf{X}}(k+1 \mid k)] \tag{56}$$

for $k = 0,1,2,\ldots$, where $\hat{\mathbf{X}}(0 \mid 0) = \mathbf{0}$. $\hat{\mathbf{X}}(0 \mid 0)$ is set equal to zero since the expectation of $\mathbf{X}(0)$ is zero.

$\mathbf{G}(k+1)$ is an n x m matrix , called the Kalman Gain Matrix which is specified by the realtions:

$$\mathbf{P}(k+1 \mid k) = \mathbf{A}\mathbf{P}(k \mid k)\mathbf{A}^T + \mathbf{B}\mathbf{n}\mathbf{Q}(k)\mathbf{B}\mathbf{n}^T \tag{57}$$

$$\mathbf{G}(k+1) = \mathbf{P}(k+1 \mid k)\mathbf{C}^T[\mathbf{C}\mathbf{P}(k+1 \mid k)\mathbf{C}^T + \mathbf{R}(k+1)]^{-1} \tag{58}$$

$$\mathbf{P}(k+1 \mid k+1) = [\mathbf{I} - \mathbf{G}(k+1)\mathbf{C}]\mathbf{P}(k+1 \mid k) \tag{59}$$

$\mathbf{P}(k \mid k)$ is the covariance matrix of the error between the states and their estimates

$$\mathbf{P}(k \mid k) = \mathrm{E}\{[\mathbf{X}(k) - \hat{\mathbf{X}}(k \mid k)][\mathbf{X}(k) - \hat{\mathbf{X}}(k \mid k)]^T\} \tag{60}$$

Since we are using the steady state gains the choice of $\mathbf{P}(0 \mid 0)$ is irrelevant. $\mathbf{P}(0 \mid 0)$ is initialized to zero in the gain derivation program for simplicity [Ref. 6: p. 139-140].

C. STEADY-STATE SOLUTION

If Equations (57), (58), and (59) are repeatedly iterated, $\mathbf{G}(k+1)$ will converge to a steady state value [Ref. 7: p. 263].

$$\mathbf{G}_{ss} = \lim_{k \to \infty} \mathbf{G}(k+1) \tag{61}$$

The values of $\mathbf{G}_{ss}$ (or $\mathbf{G}$) can be substituted into Eq. (56) making the steady state Kalman filter

$$\hat{\mathbf{X}}(k+1 \mid k) = \mathbf{A}\hat{\mathbf{X}}(k \mid k) + \mathbf{B}\mathbf{U}(k) \tag{62}$$

$$\hat{\mathbf{X}}(k+1 \mid k+1) = \hat{\mathbf{X}}(k+1 \mid k) + \mathbf{G}[\mathbf{Y}(k+1) - \mathbf{C}\hat{\mathbf{X}}(k+1 \mid k)] \tag{63}$$

D. OBSERVER PERFORMANCE

The performance of an observer is judged by how accurately and rapidly it estimates the desired states. The performance measure of the observer as a whole is shown in equation (54). The normalized performance of the observer for individual states is

$$\mathbf{J}_i = \mathrm{E}[(x_i - \hat{x}_i)^2]/\mathrm{E}[x_i^2] \tag{64}$$

which can be found using Eq. (65)

$$\mathbf{J}_i = \sum_{k=0}^{\infty} (x_i(k) - \hat{x}_i(k))^2 T_s \div \sum_{k=0}^{\infty} x_i^2(k) T_s \tag{65}$$

$\mathbf{J}_i$ = performance measure for the *ith* state

$x_i(k)$ = value of the *ith* state at k

$\hat{x}_i(k)$ = observer estimateof *ith* state at k

T_s = sample interval

A normalized performance measure is used to aid comparison of the performance of the observer in estimating various states. From Eq. (65) it can be shown that if $\hat{x}_i(k) = 0$ for all $k = 0,1,2,...$ that $\mathbf{J}_i$ would be unity. Therefore, the better the performance of the observer, the smaller the fraction of one $\mathbf{J}_i$ will be.

IV. SIMULATION

A. INTRODUCTION

The objectives of the simulation were to

- determine the sensitivity of the observer performance and settling time to changes in the ratio of plant noise to measurement noise,
- determine the effect on observer performance and settling time of increasing the number of modes observed in the matched plant/observer, and
- determine the performance for the reduced order observer.

B. PLANT AND OBSERVER DATA

The dynamic model is a truncated form of a preliminary space station configuration; the phase II dual keel structure.[1] The full model consists of an infinite number of natural modes but this was restricted to the first ten active modes for this study due to limitations on computer resources. As will be shown reasonable data can be obtained with this simplification in examining the observer performance.

C. SIMULATION PROGRAMS

The simulation was broken down into two segments due to the large memory and computational time requirements. The first program computed the steady state observer gain matrix (G). The second program ran the observer and the plant when the plant was subjected to an impulse excitation.

The steady state observer gain matrix (G) was obtained by repeated iteration of equations (57), (58), and (59). The equations were were run until the values of the matrix changed by less than a set fraction. The following formula was used to check the changes in the gain matrix elements

$$\Delta g_{i,j} = [g_{i,j}(k+1) - g_{i,j}(k)]/g_{i,j}(k+1) \tag{66}$$

The program was terminated when $\delta g_{i,j}$ was less than 10^{-10} .

The settling time for the estimates of the states to be within 2% of the actual states was determined by finding the eigenvalues of A - G*C then computing as follows [Ref. 6: p. 139-143]

---

1 The model for preliminary station configuration was provided courtesey of McDonnel Douglas Astronautics Company, 5301 Bolsa Avenue, Huntington Beach, CA 92647.

$$T_s = \log(.02)/\log(\lambda_{AGC_{min}}) \quad (67)$$

The expected error in the sensor, i.e., the standard deviation of the noise in the measurement, was choosen as 10^{-3} feet per sec. per sec. based on the natural frequencies in the structure and reasonable sensor sensitivity [Ref. 2: p. 79-80]. The expected plant noise was varied to find the range of ratios between plant and measurement noise that the filter would be effective. This approach was taken since the plant noise contributors are not currently well defined.

The second program subjected the plant as modeled in Eq. (45) to an impulse excitation and then had the observer estimate the selected states using observer equations (62) and (63). Observer performance was computed using Eq. (65).

A third program was used to find the contribution of unobserved modes to the noise in the Kalman observer. The program ran the plant subject to an impulse excitation and computed the product of the measurement matrix **C** times the unobserved modes of the state vector $\mathbf{X}(k)$ for a measure of the noise contributed by the unobserved modes.

The three programs are listed in the appendices.

D. EFFECT OF PLANT TO MEASUREMENT NOISE RATIO ON OBSERVER PERFORMANCE

The ratio of the variance of the plant noise (PN) to the variance of the measurement noise (MN) was found to have a strong effect on the Kalman Observer performance (J) and settling time (T_s) . Figures 1 through 6 show the observer performance for a 3 mode matched plant and observer system for progressively smaller PN/MN ratios.[2] Figure 7 shows the performance for the seventh mode (position) versus several values of PN/MN. Figure 8 is the settling time versus the same PN/MN ratios.

The figures show that, for all of the plotted performance values, the observer performance is at least marginally acceptable regardless of the PN/MN ratio. Decreasing the PN/MN ratio leads to an even more rapid degradation in observer performance. The settling times also rapidly increase as the PN/MN ratio decreases.

---

2 Figures 1-6 and 9-15 show the performance measure for each mode. The bar for the mode position is immeadiately to the right of the numbered tick mark on the x-axis scale, the mode velocity is next to it immeadiately adjacent to the tick mark without a number.

E. EFFECTS OF INCREASED MODES ON OBSERVER PERFORMANCE

The matched plant/observer was run with increasing numbers of modes to see if there was an effect on observer performance (J) or settling time T_s. Figures 7 through 17 are of observer performance for systems with increasing numbers of modes in the system being observed. Figure 18 is of settling time versus the number of modes in the system. The ratio of PN/MN was kept constant at PN/MN = 2.5×10^9.

The increasing of the number of modes for the matched plant/observer had neglible effect on the performance for the individual modes. The performance value for the modes was effectively constant. Settling times for the observers increased as the number of modes was increased.

F. REDUCED ORDER KALMAN OBSERVER

The Kalman Observer has been shown to be effective where the number of modes observed matches the number of modes in the plant. The Kalman Observer was then run with the one less mode observed than the number of modes in the plant. The gain matrix (G) from the matched system was used. The observer failed with the state estimates produced by the observer becoming excessively large and having settling times of hours vice minutes. Since the purpose of the observer was to provide estimates for use in controlling the plant the time delay makes the estimates unusable.

The cause of the observer failure is apparent when you look at the last portion of Eq. (56) of the Kalman Observer

$$\mathbf{G}[\mathbf{Y}(k+1) - \mathbf{C}\hat{\mathbf{X}}(k+1 \mid k)] \tag{68}$$

This portion of the observer equation is the correction of $\hat{X}(k+1 \mid k)$ to produce $\hat{X}(k+1 \mid k+1)$. The design of the Kalman observer is to produce an estimate despite the measurement noise but, with the reduced order filter there is additional unanticipated noise which causes over correction of the values of $\hat{X}$ leading to the state estimates being excessively large and settling times being too long. This can be shown by examining what composes $Y(k+1) - CX(k+1 \mid k)$

$$\mathbf{C}\begin{bmatrix} x_1(k) \\ x_2(k) \\ \uparrow \\ \downarrow \\ x_{m-1}(k) \\ x_m(k) \\ \text{---} \\ x_{m+1}(k) \\ x_{m+2}(k) \\ \uparrow \\ \downarrow \\ x_{n-1}(k) \\ x_n(k) \end{bmatrix} - \mathbf{C}\begin{bmatrix} \hat{x}_1(k) \\ \hat{x}_2(k) \\ \uparrow \\ \downarrow \\ \hat{x}_{m-1}(k) \\ x_m(k) \\ \text{---} \\ 0 \\ \uparrow \\ \downarrow \\ 0 \end{bmatrix} \tag{69}$$

$\mathbf{C}$ times the state $x_{m-1}(k)$ through $x_n(k)$ is unanticipated noise so if

$$\mathbf{C}\begin{bmatrix} x_1(k) \\ x_2(k) \\ \uparrow \\ \downarrow \\ x_{m-1}(k) \\ x_m(k) \end{bmatrix} - \mathbf{C}\begin{bmatrix} \hat{x}_1(k) \\ \hat{x}_2(k) \\ \uparrow \\ \downarrow \\ \hat{x}_{m-1}(k) \\ \hat{x}_m(k) \end{bmatrix} = \mathbf{0} \tag{70}$$

the remaining portion of the C matrix times the modal states is an equivalent noise.

Table (1) shows the growth of the unanticipated noise in the filter as the number of unobserved modes in the plant grows. Table (2) shows the individual contributions of the individual modes when left unobserved. Table (1) shows that the unanticipated noise is much larger than that expected by the filter (10^{-3}). Table (2) shows that there are modes that do not markedly contribute to the noise and that they might successfully be left unobserved if the measurement noise estimate was already much larger than these noise sources.

Table 1. CUMULATIVE UNANTICIPATED NOISE FROM UNOBSERVED MODES

Number of Unobserved Modes	Unobserved Modes	E1	E2	E2
1	10	0.647	97.440	3.277
2	10-11	366.354	95.764	3.142
3	10-12	366.355	95.764	3.142
4	10-13	365.565	95.855	3.143
5	10-14	365.426	96.032	5.704
6	10-15	144195.7	116.205	2201.94
7	10-16	148006.8	170.142	5475.21
8	10-17	473974.3	39424.1	5692.50
9	10-18	474344.2	60078.8	9419.77
10	10-19	474358.5	68987.7	9865.27

Table 2. UNANTICIPATED NOISE FROM UNOBSERVED MODES BY MODE

Unobserved Mode	E1	E2	E3
10	0.64716	97.4403	3.27761
11	359.342	0.20929	0.21429
12	0.9353E-08	0.1364E-07	0.2196E-07
13	0.3852E-02	0.4409E-02	0.9017E-03
14	0.5615E-03	0.2592E-01	2.57554
15	143090.9	17.9682	2167.02
16	195.736	83.3458	5675.91
17	324471.2	39252.26	221.170
18	216.240	21133.6	3736.93
19	7.69298	8829.95	458.504
20	2.3194	3949.16	108.981

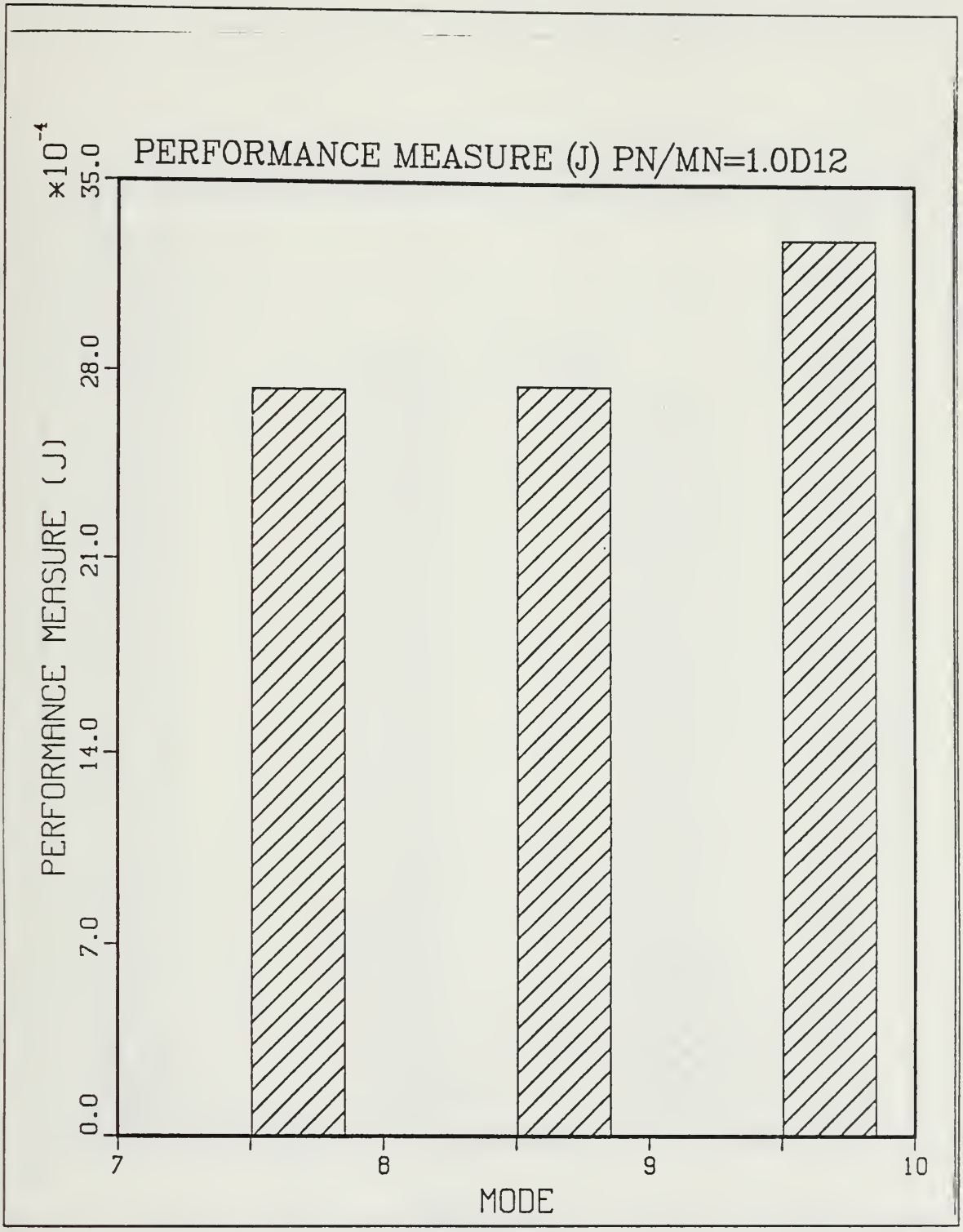

Figure 1. Observer Performance (J) PN/MN = 1.0d12

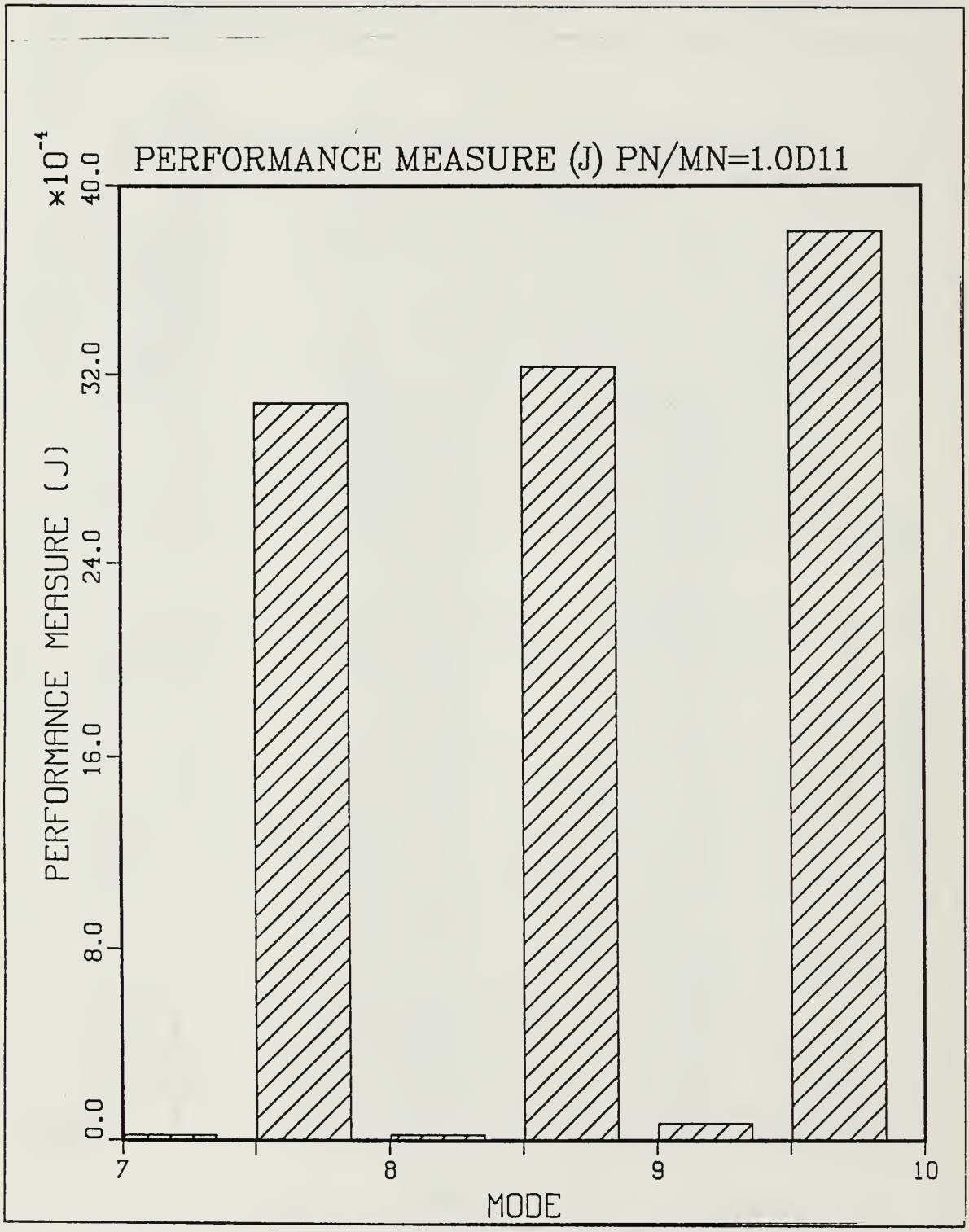

Figure 2. Observer Performance (J) PN/MN = 1.0d11

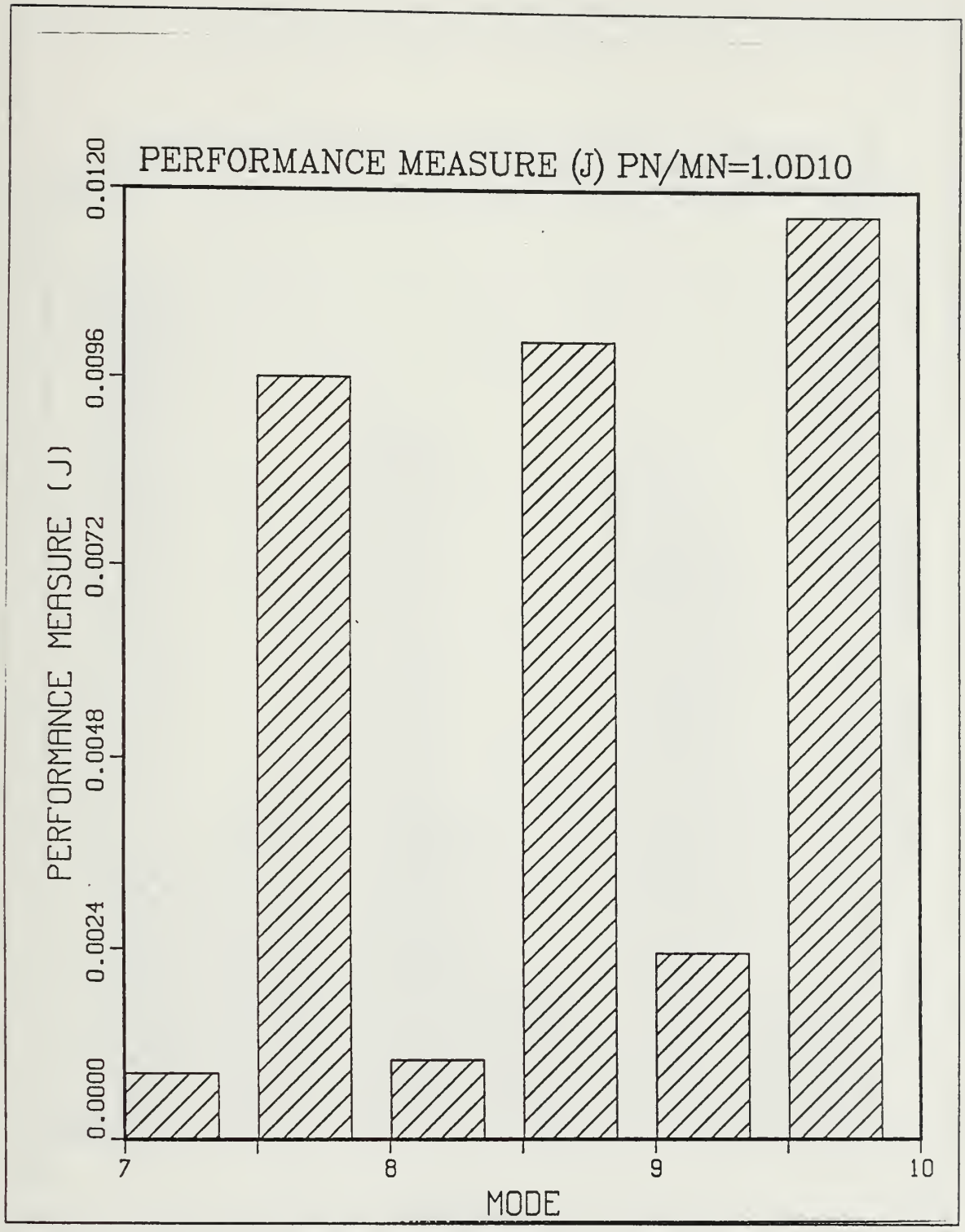

Figure 3. Observer Performance (J) PN/MN = 1.0d10

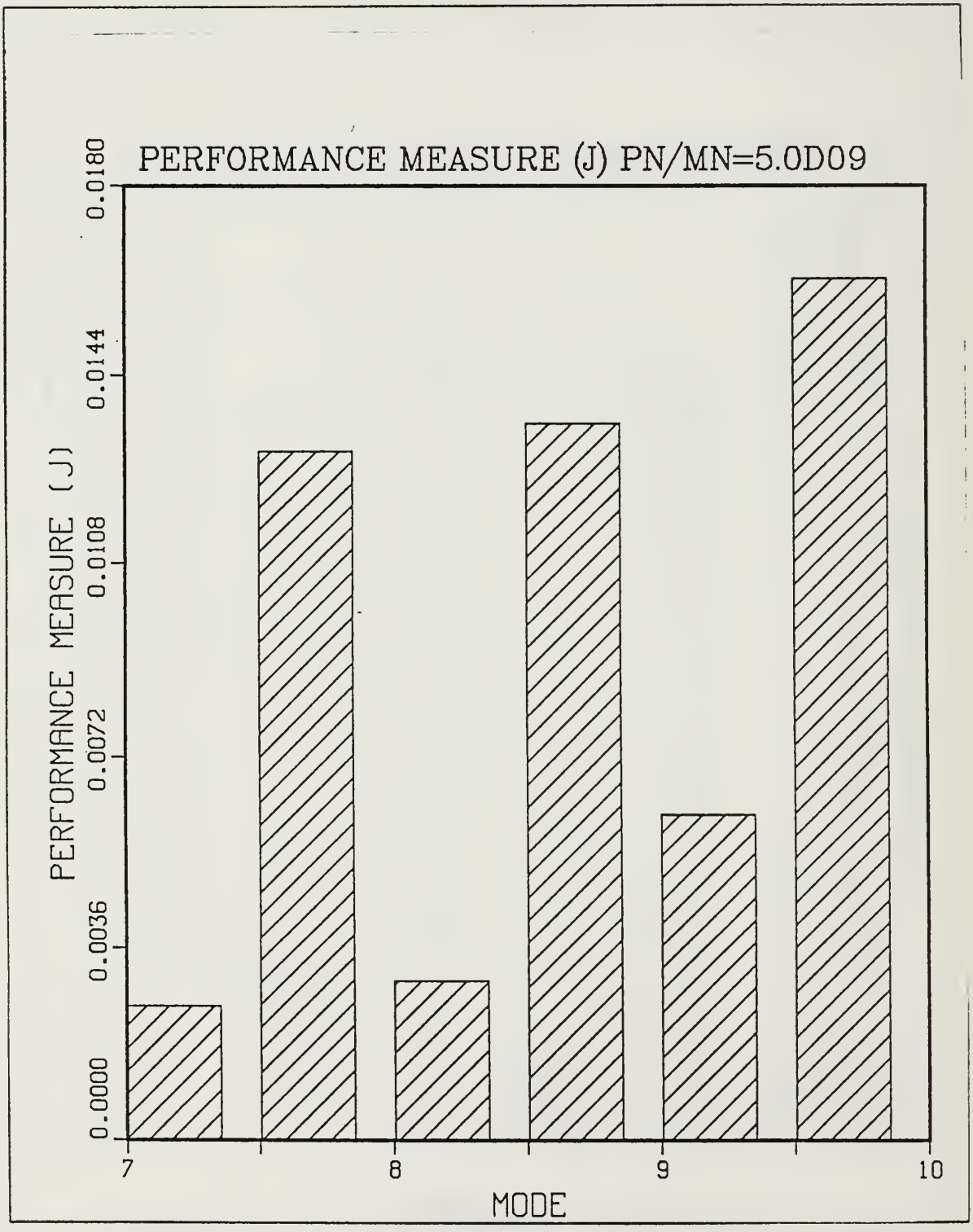

Figure 4. Observer Performance (J) PN/MN = 5.0d09

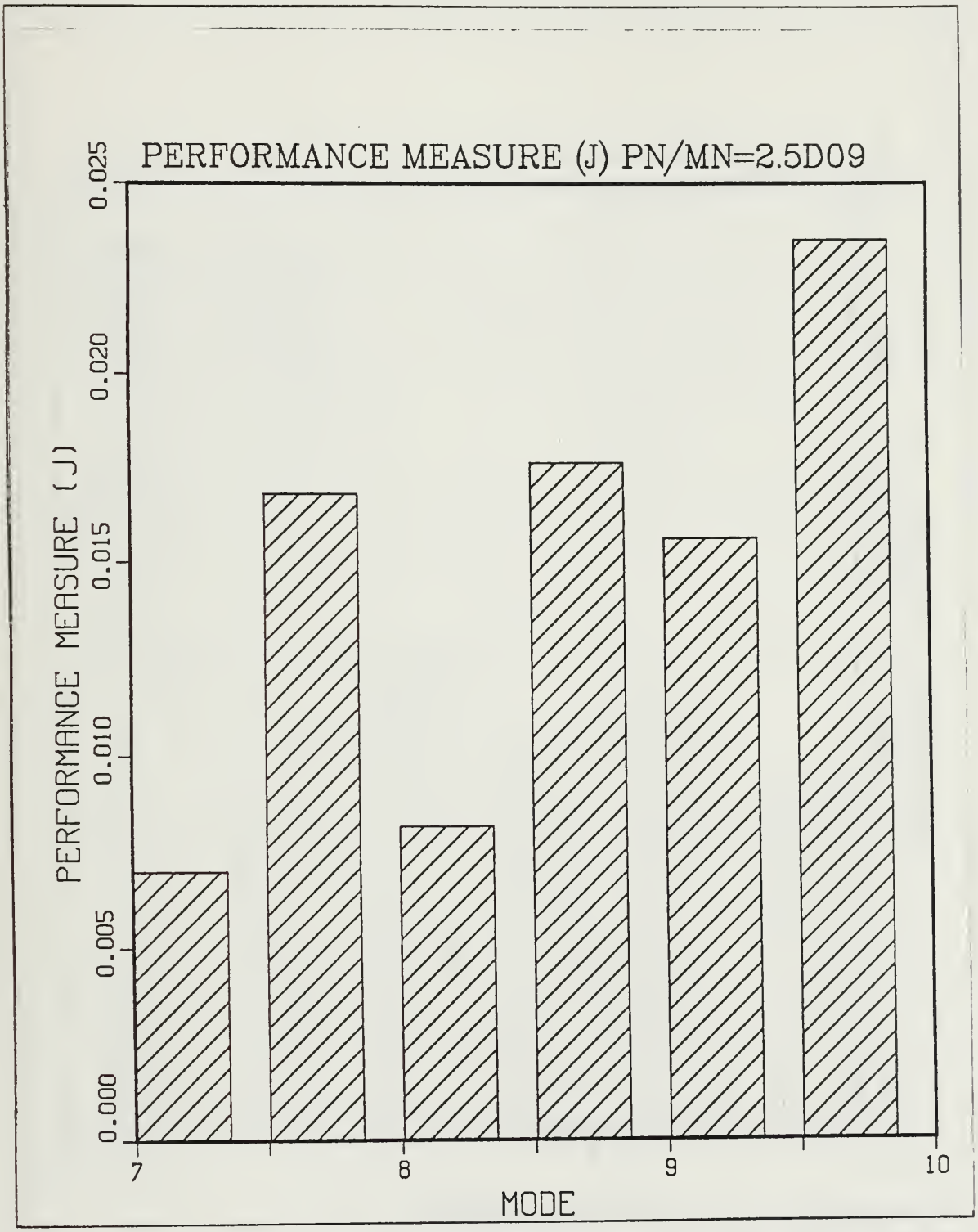

Figure 5. Observer Performance (J) PN/MN = 2.5d09

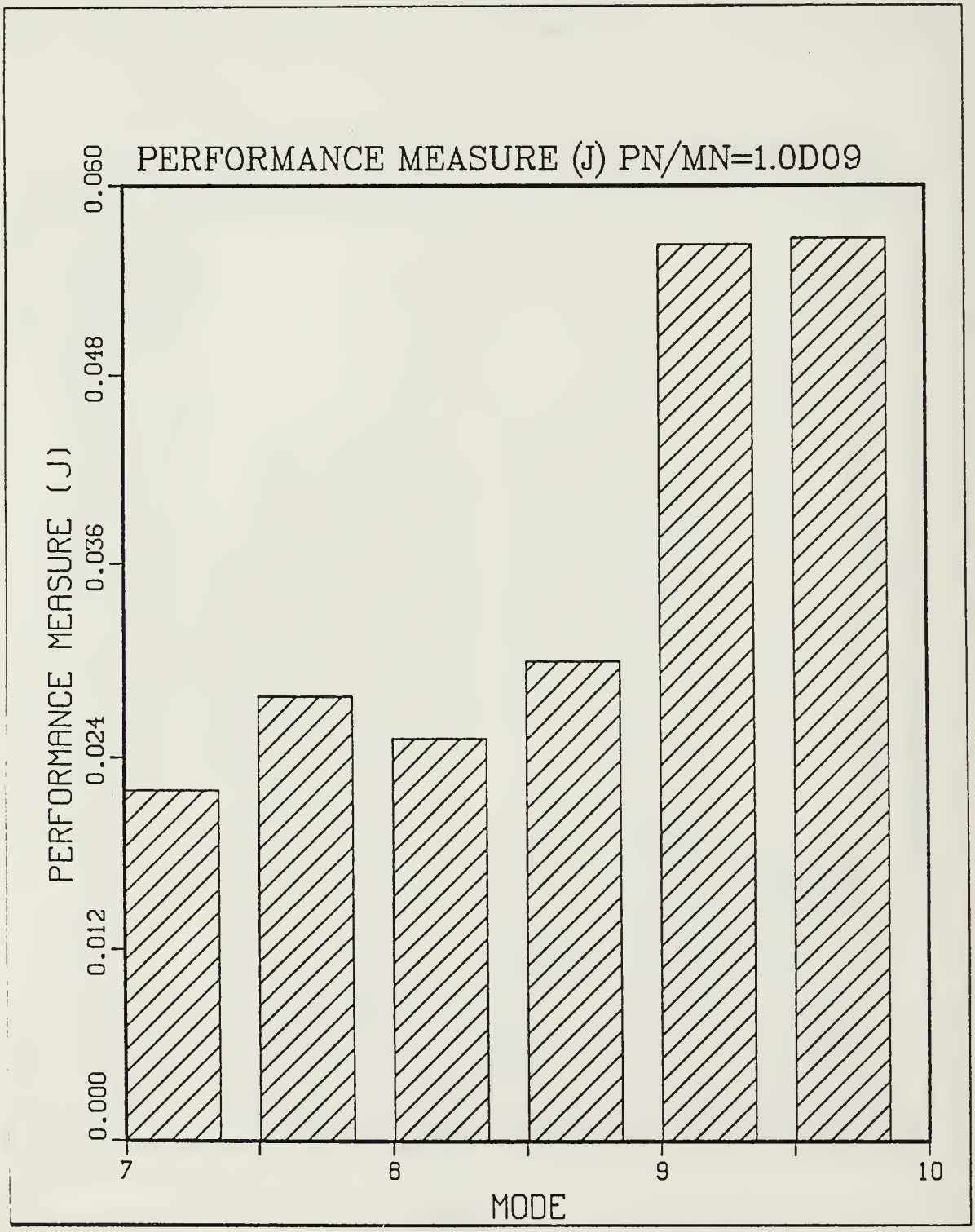

Figure 6. Observer Performance (J) PN/MN = 1.0d09

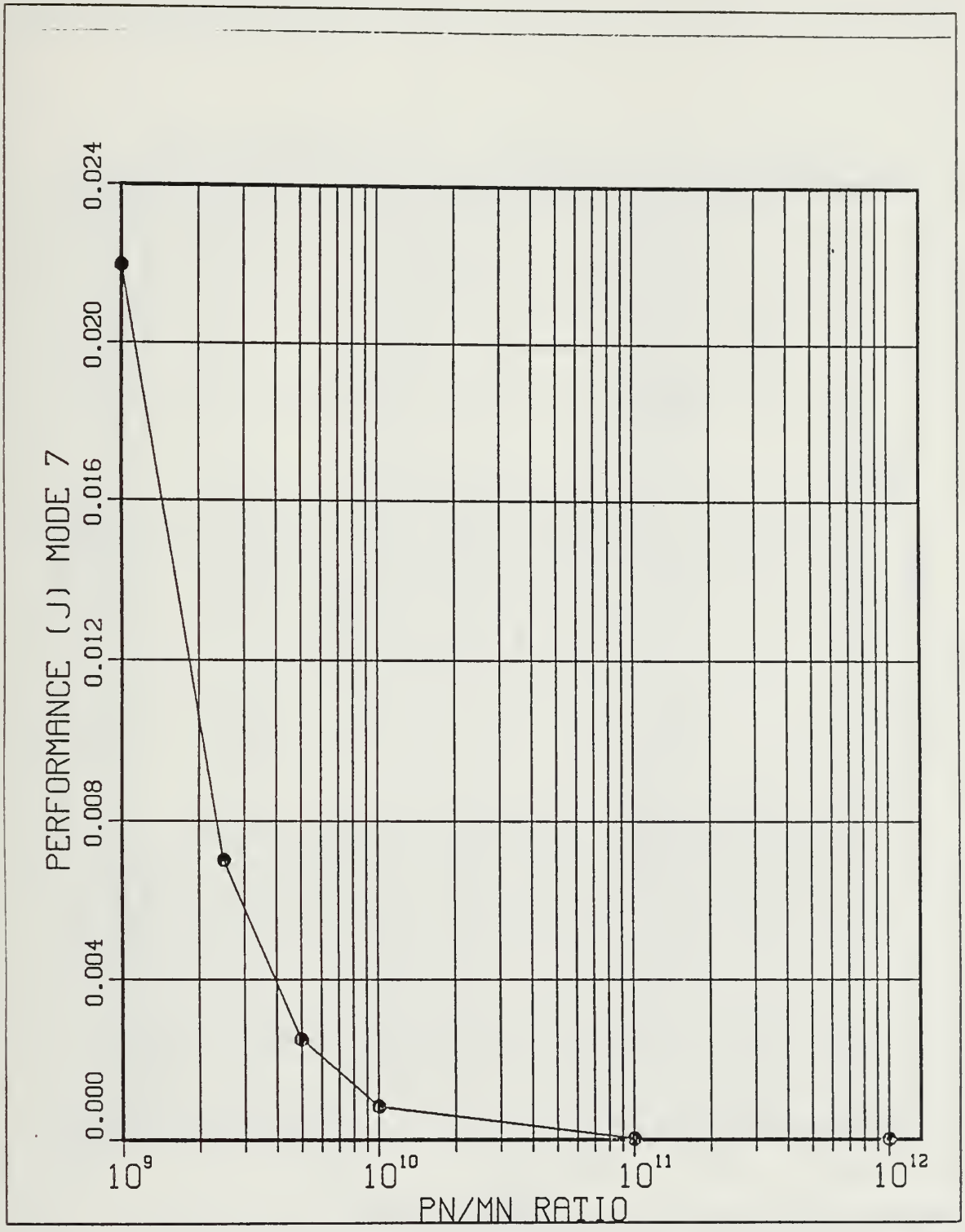

Figure 7. Mode 7 (Postion) Observer Performance versus PN/MN

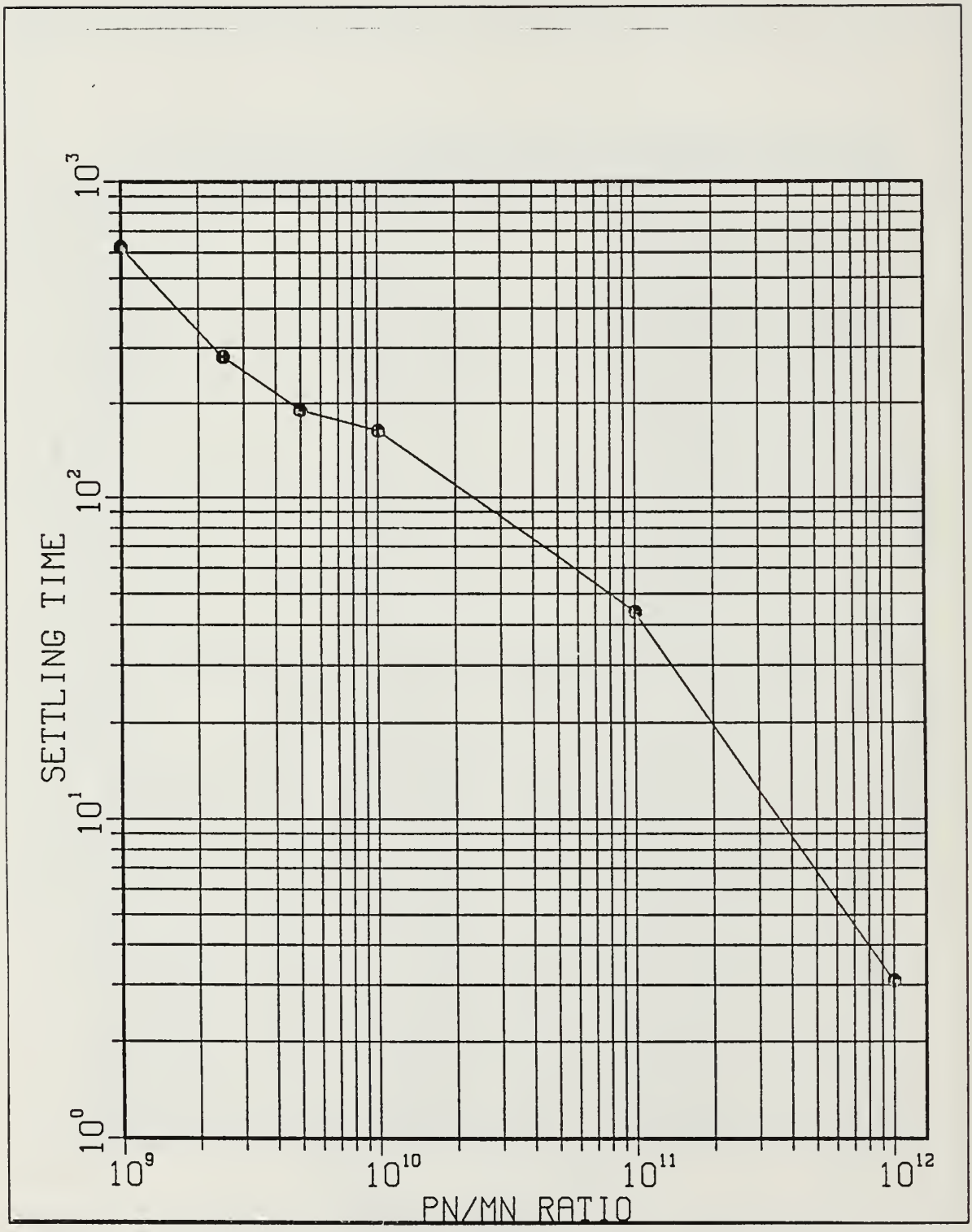

Figure 8. Settling Time versus PN/MN

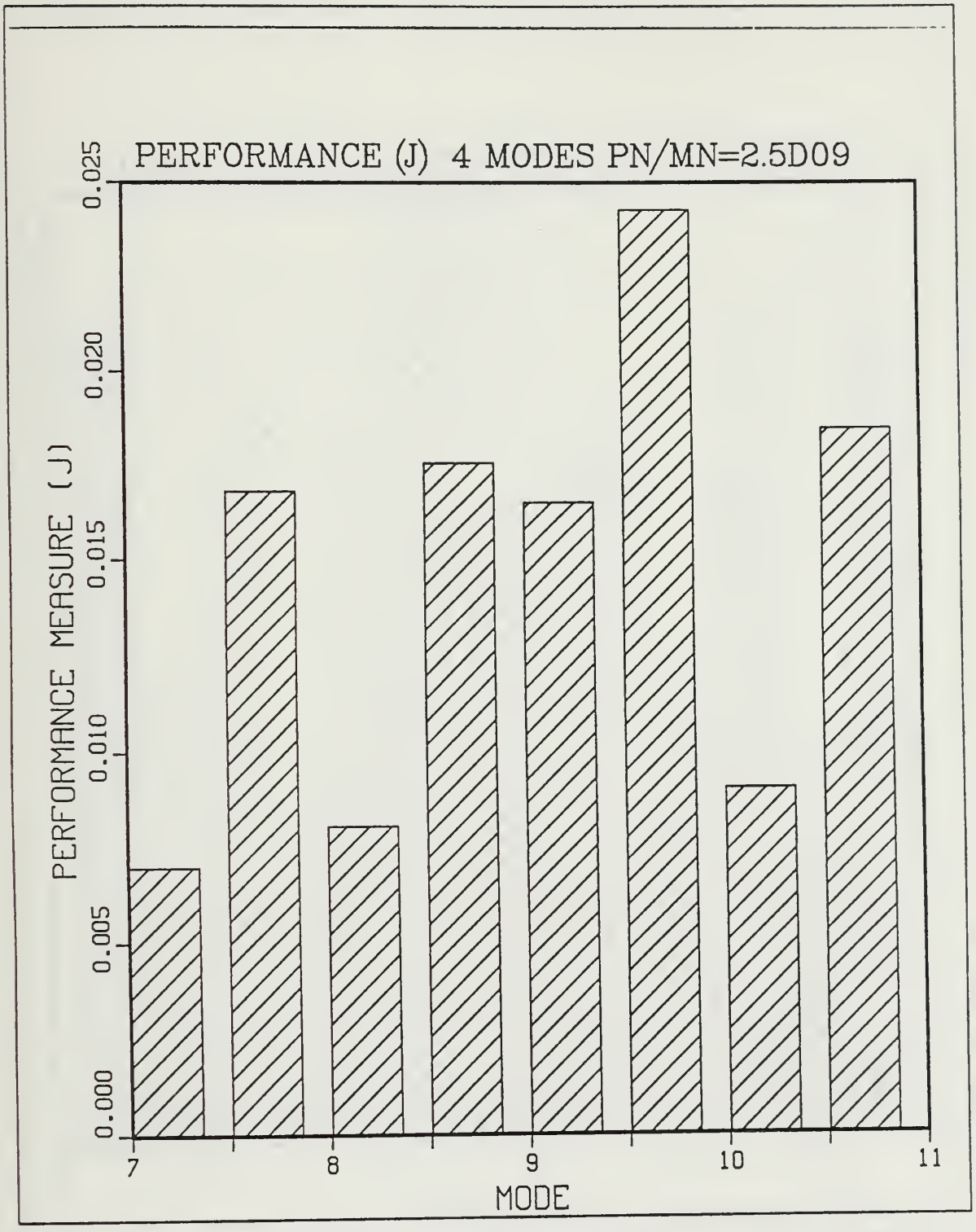

Figure 9. Observer Performance (J) 4 Modes (7 - 10)

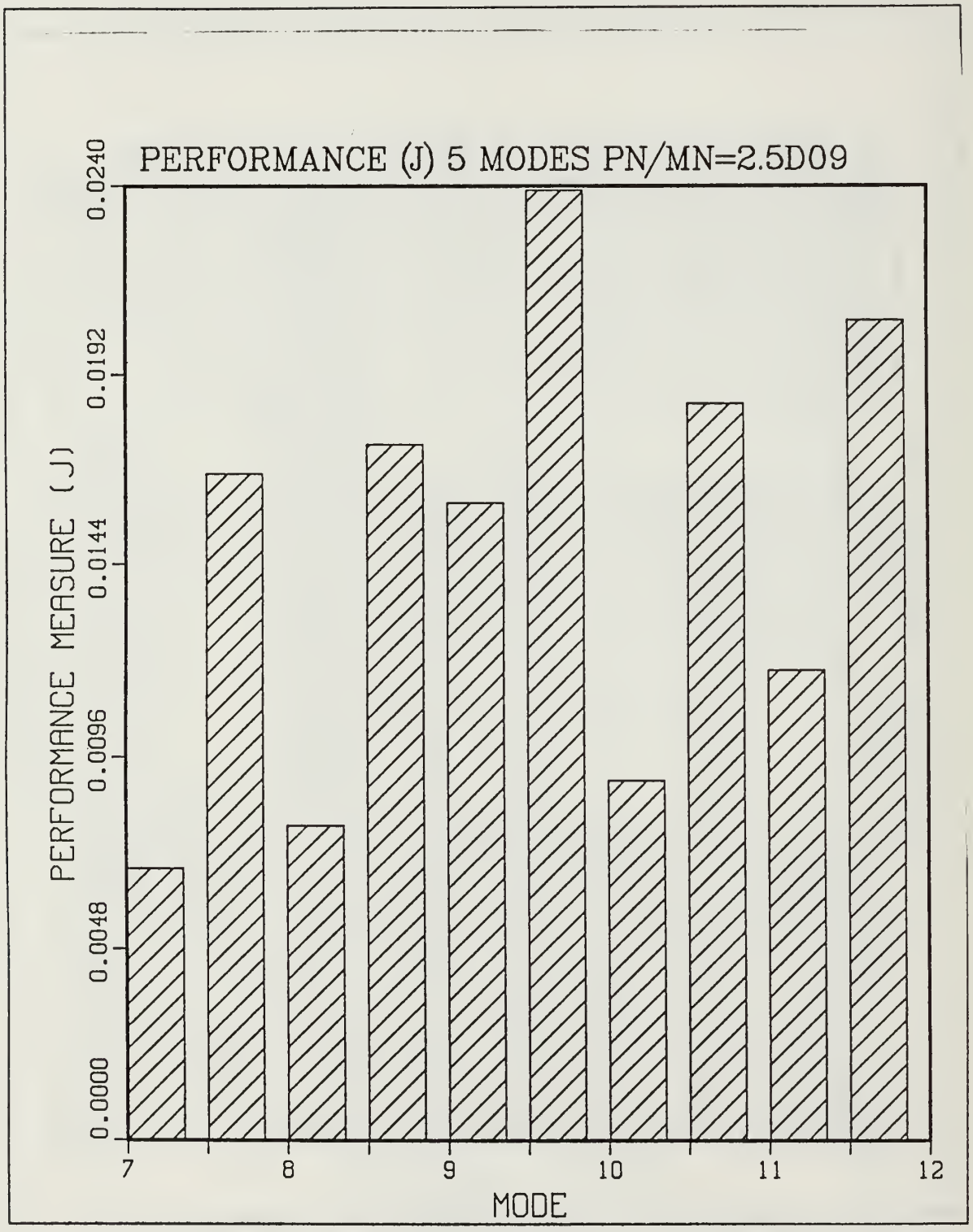

Figure 10. Observer Performance (J) 5 Modes (7 - 11)

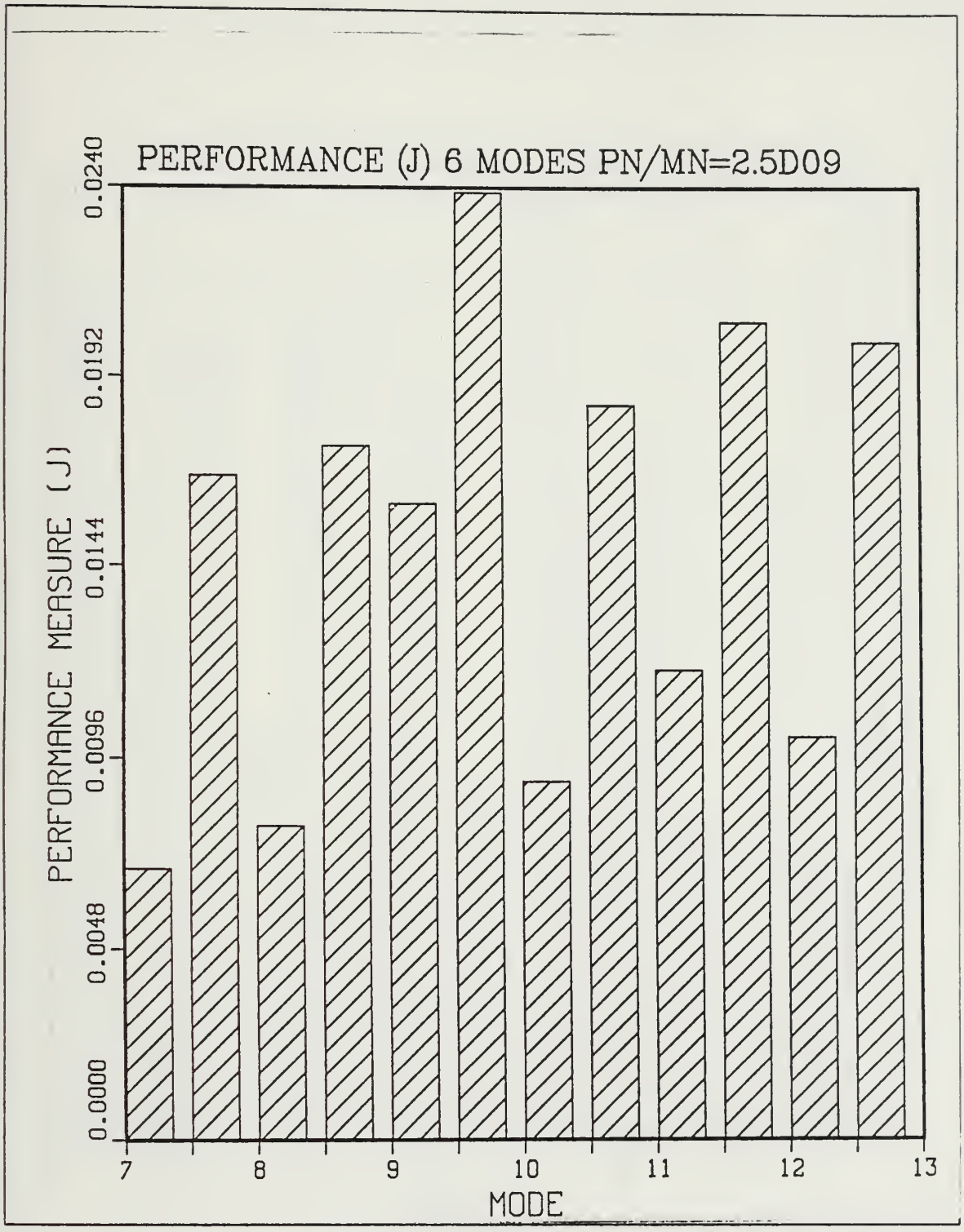

Figure 11. Observer Performance (J) 6 Modes (7 - 12)

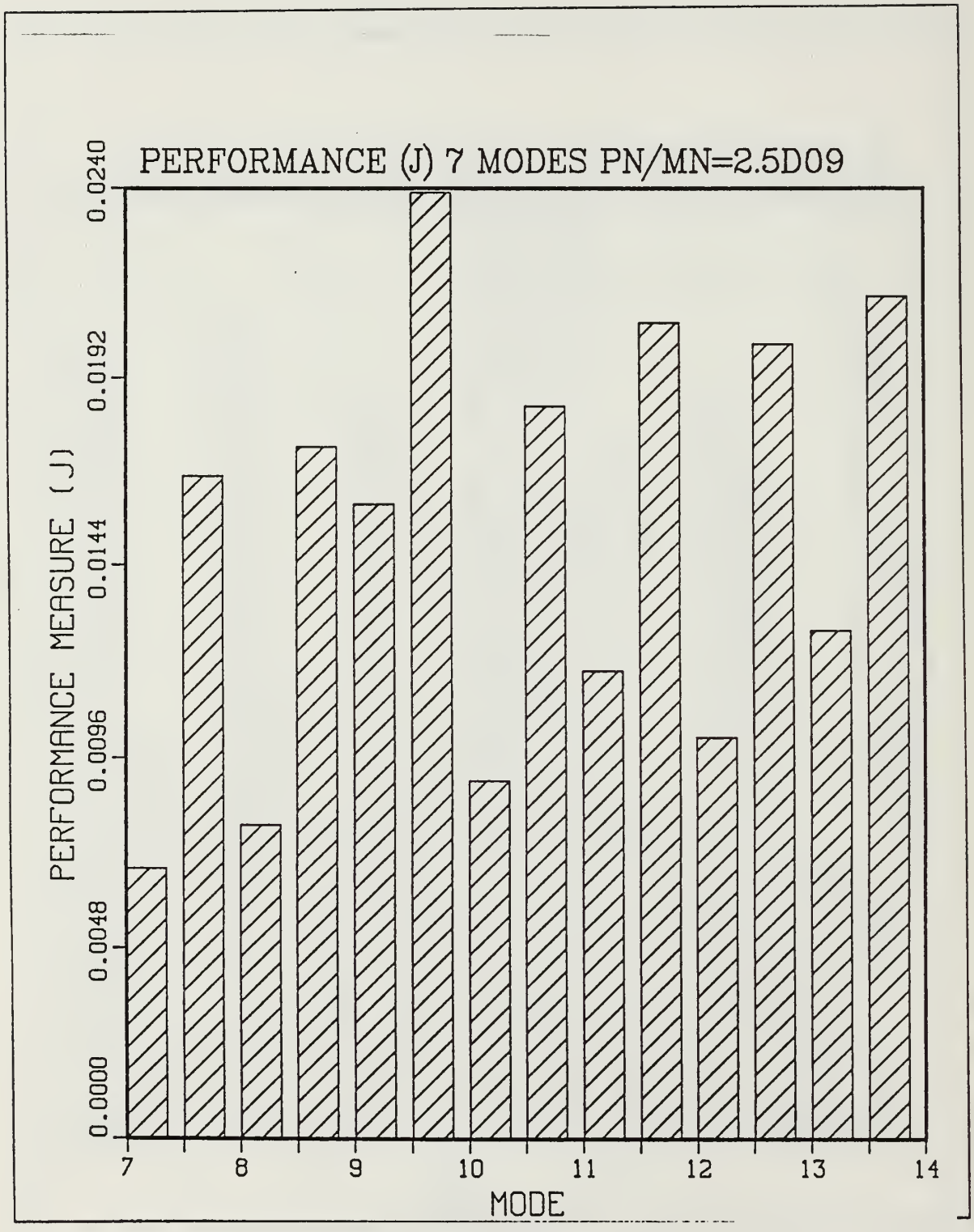

Figure 12. Observer Performance (J) 7 Modes (7 - 13)

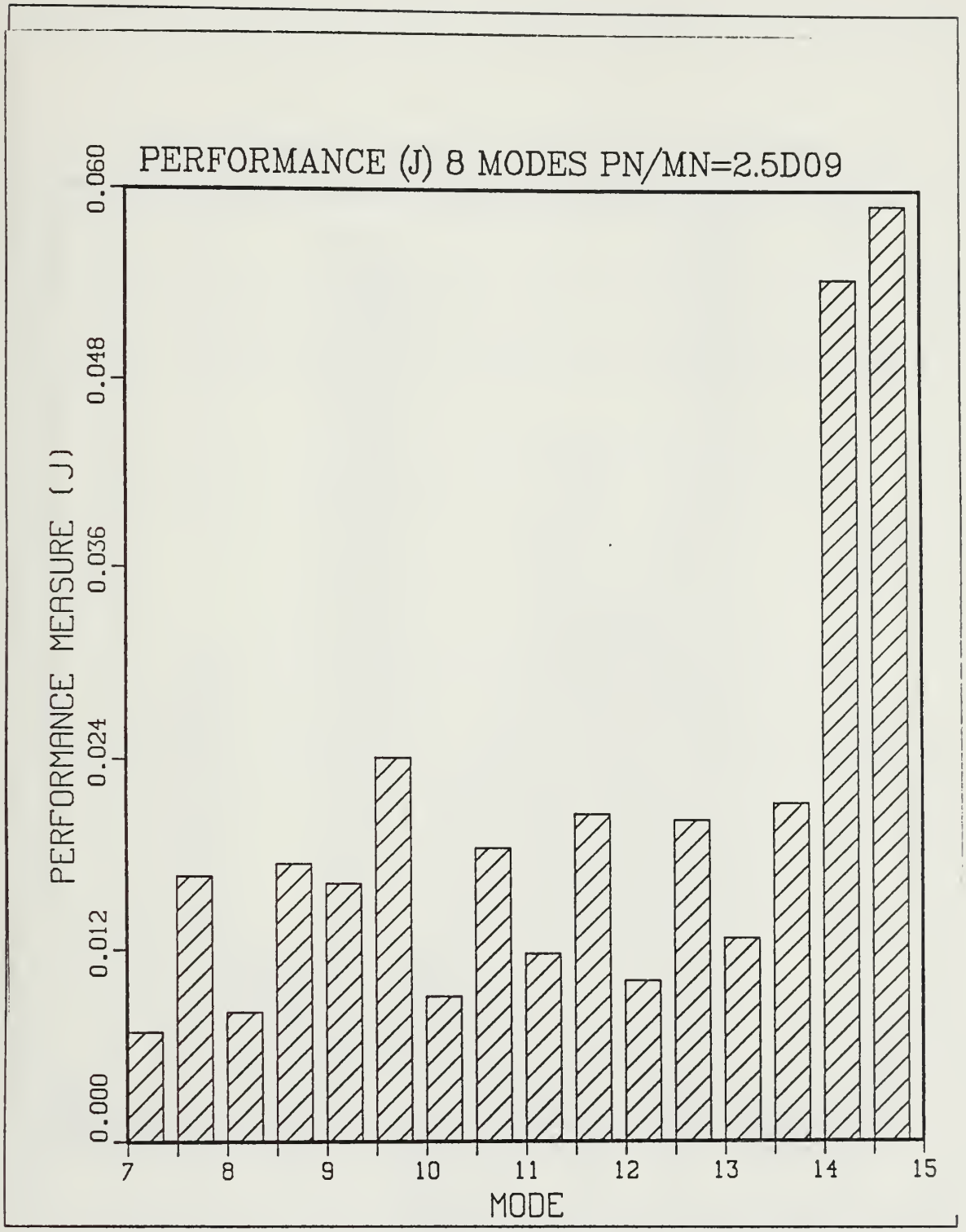

Figure 13. Observer Performance (J) 8 Modes (7 - 14)

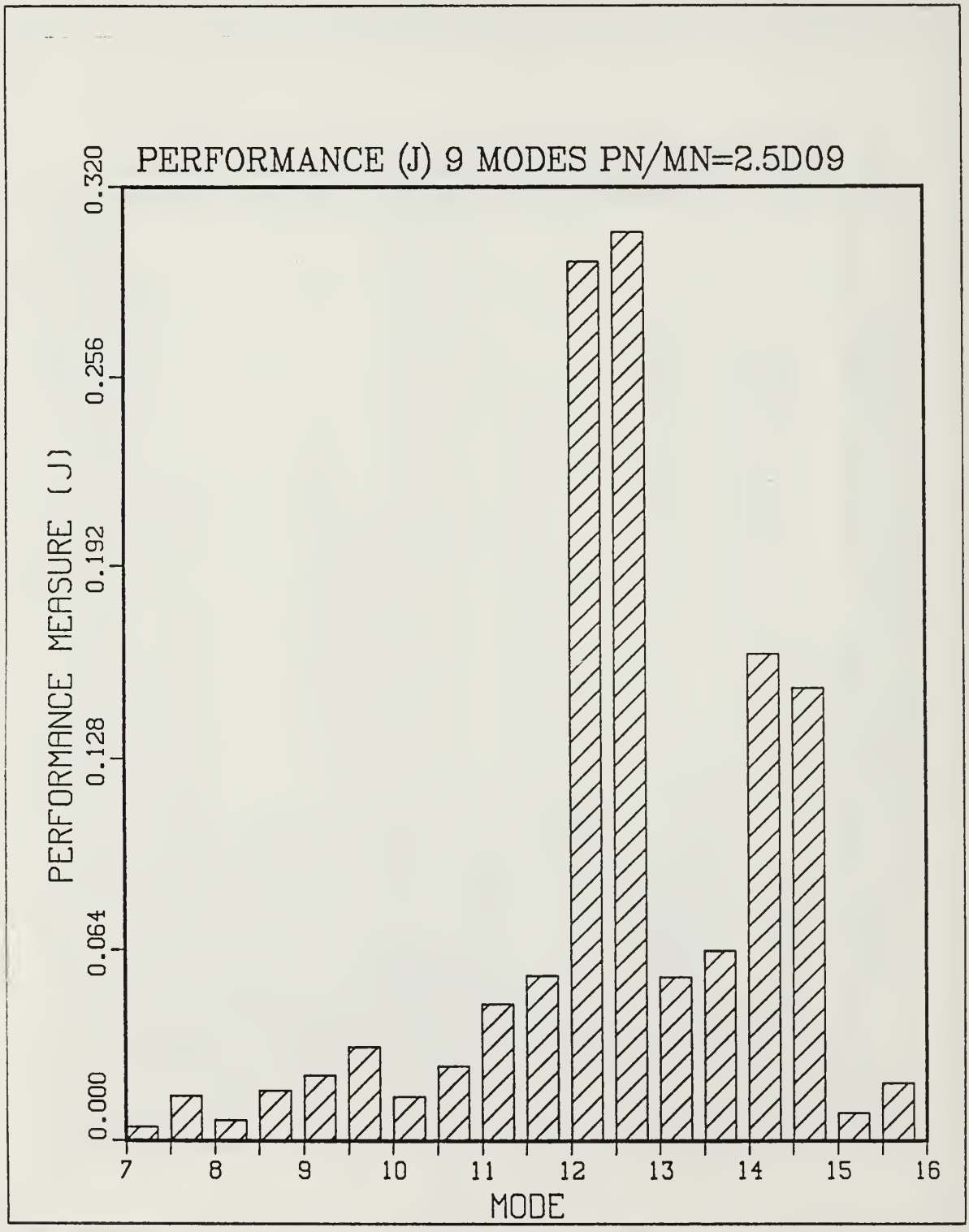

Figure 14. Observer Performance (J) 9 Modes (7 - 15)

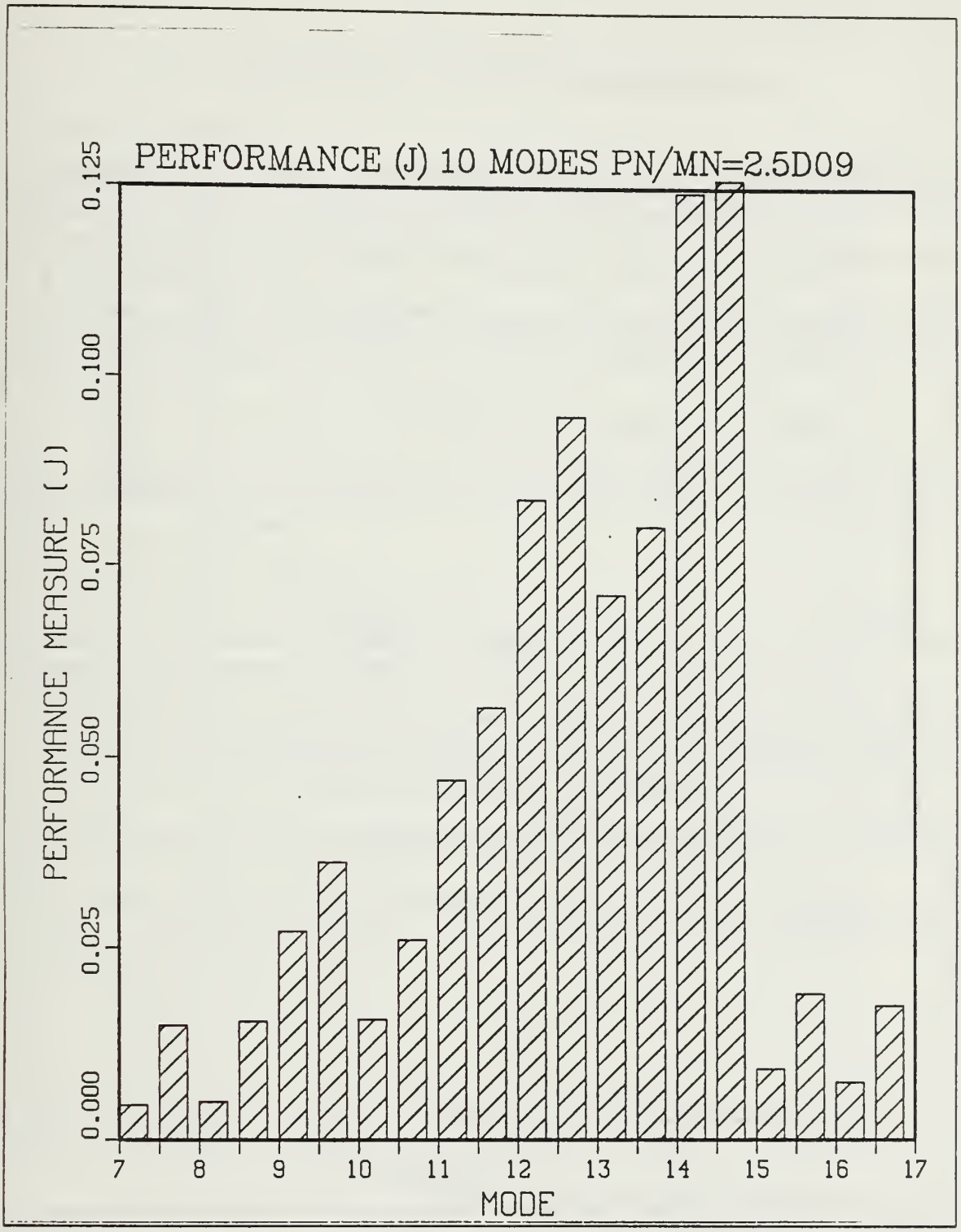

Figure 15. Observer Performance (J) 10 Modes (7 - 16)

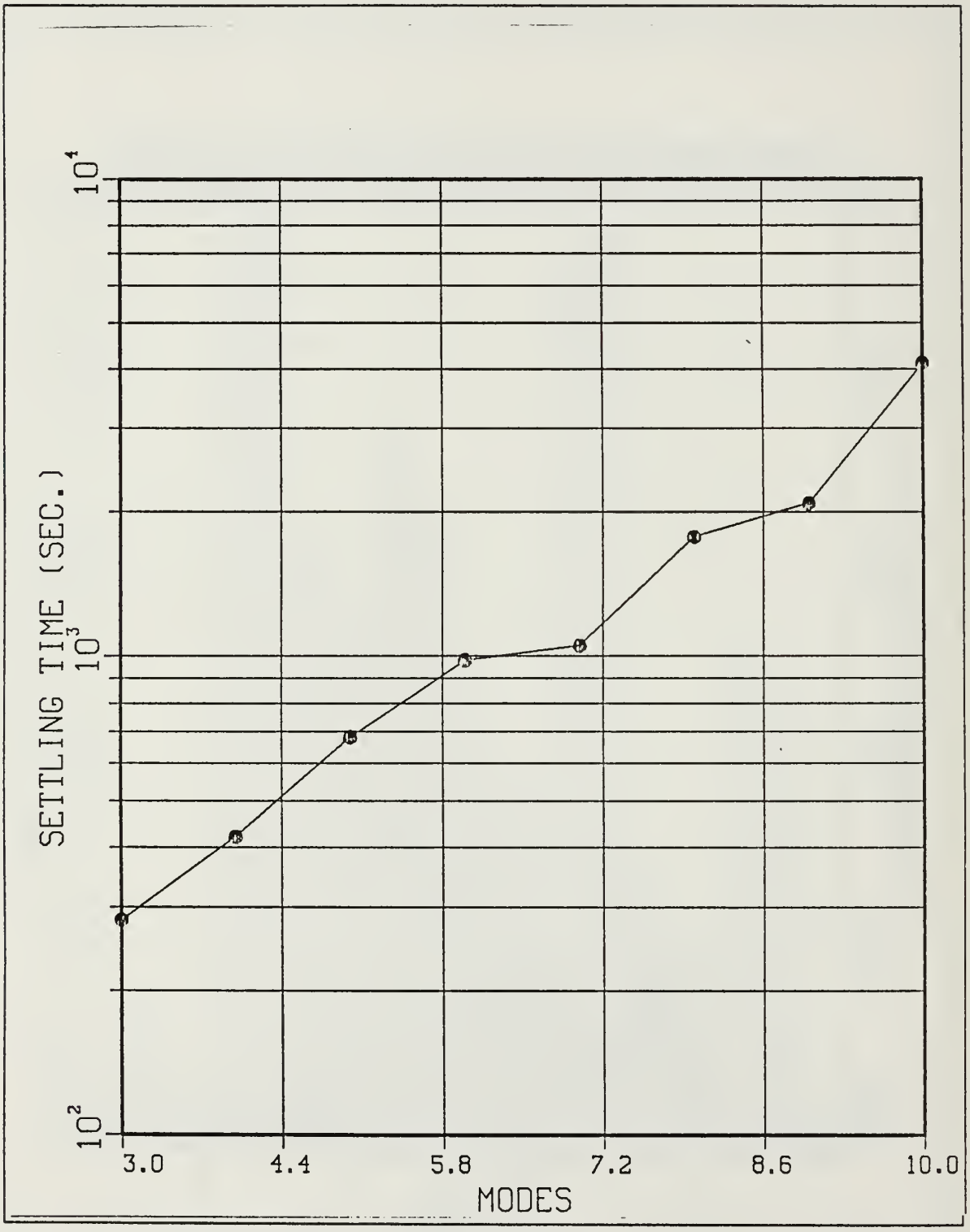

Figure 16. Settling Time versus number of Modes Observed

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Simulations runs showed that a matched plant/observer can work if the following criterions are meet:

- The ratio of plant noise to measurement noise is sufficiently high to produce a usable settling time.
- Sufficient computational power is available to run the matched observer. The amount of memory and number of computation goes up as the number of modes observed increases.

Utilizing a reduce order observer for an arbitrarily selected set of modes is not feasible. The non-observed modes add so much noise to the system that settling times and observer performance are so poor as to render the observer useless for obtaining state values for plant control.

B. RECOMENDATIONS

The work on the Kalman Observer for Large Space Structures lead to the following recommendations for further research:

- Identify those modes that contribute the largest noise to the Kalman observer and set the observer to estimate these states in addition to those required for plant control. A possible method for identifying the modes that contibute the largest noise to the observer would be the Karhunen-Loeve expansion.
- Modifying the plant/observer to model the use of sensors at additional positions to see if the increase in the data rate will help decrease settling time.
- Modify the model to incorporate noise injection into more than one location . The current model has noise injected at only one position, a useful simplification for initial analysis but not realistic.

APPENDIX A. KALMAN GAIN MATRIX GENERATION PROGRAM

```
C                                                                       GMA00010
C     ***************************************************************** GMA00020
C     ******                    GGAIN                            ****** GMA00030
C     ******  ADAPTED TO RUN KALMAN FILTER AND COMPUTE THE       ****** GMA00040
C     ******  G MATRIX BY ITERATION STOPPING WHEN THE            ****** GMA00050
C     ******  THE MATRIX GOES TO STEADY STATE                    ****** GMA00060
C     ***************************************************************** GMA00070
C                                                                       GMA00080
C                                                                       GMA00090
C     ***************************************************************** GMA00100
C     ******              VARIABLE DECLARATIONS                  ****** GMA00110
C     ***************************************************************** GMA00120
C                                                                       GMA00130
      EXTERNAL STMTRX,DLINRG,EXCMS, DEVCRG                              GMA00140
      CHARACTER*6 NAM                                                   GMA00150
      CHARACTER*1 AGAIN,CORECT,RAGAIN                                   GMA00160
      INTEGER ROWN1,ROWN2,ROWN3,COUNT,NODE,MODE,KQ,EMODE,SMODE,R2M,C2M  GMA00170
      INTEGER CT,CF,KADJ,CFADJ,LOOP,PRNT,JJ,JK,N1,JR,KR,MR,ISEED,M2     GMA00180
      INTEGER JL,J1,JM                                                  GMA00190
      REAL LAMA(100), UGVEX(684,100),RNODE,RMODE,MIN                    GMA00200
      REAL*8 PHI(2,2,100),GAMMA(2,100),EGT,GMA,WN,W1,X1T,X2T,TIME       GMA00210
      REAL*8 A(200,200),B(200,3),F(3, 50),IMPLSE,ENERGY                 GMA00220
      REAL*8 COSW1T,SINW1T,X1(100),X2(100),COST(100)                    GMA00230
      REAL*8 DAMP,SAMPT,PI,SAMPTM,SUM1,SUM2,SUM3,SUMC                   GMA00240
      REAL*8 C(6,200), IDENT( 50, 50), RMN(6,6), QPN(3,3)               GMA00250
      REAL*8 PK( 50, 50), Y(6), BN(200,3)                               GMA00260
      REAL*8 PNVARX, PNVARY, PNVARZ                                     GMA00270
      REAL*8 MNVX1, MNVY1, MNVZ1, SUM, BQBT(50,50)                      GMA00280
      REAL*8 TMP1( 50,3), TMP2(3,3), TMP3( 50, 50)                      GMA00290
      REAL*8 PK1( 50, 50),G( 50,3)                                      GMA00300
      REAL*8 DY(3), ES,ED,ESUM,CGN,PRT                                  GMA00310
      REAL*8 SF, N9, TCHK, ACHK, H1, H2, H3, H4, H5, H6                 GMA00320
      REAL*8 AGC(100,100)                                               GMA00330
C                                                                       GMA00340
      COMPLEX*8 EVAL(100), EVEC (100,100)                               GMA00350
C                                                                       GMA00360
C                                                                       GMA00370
C                                                                       GMA00380
C     ***************************************************************** GMA00390
C     ******              VARIABLE DEFINITIONS                   ****** GMA00400
C     ***************************************************************** GMA00410
C                                                                       GMA00420
C     STMTRX = SUBROUTINE EXTABLISHES STATE TRANSITION MATRICIES        GMA00430
C     LAMA = VECTOR OF THE SQUARE OF THE NATURAL FREQUENCIES            GMA00440
C     UGVEX = MODE POSITONS AND SLOPES OF THE NODAL POINTS              GMA00450
C     PHI = STATE TRANSITION MATRICIES FOR EACH MODE                    GMA00460
C     GAMMA = INPUT TRANSITION MATRIX                                   GMA00470
C     A = DIAGONAL MATRIX CONSISTING OF PHI                             GMA00480
C     B = INPUT MATRIX OF GAMMA AND CONTROL SLOPES                      GMA00490
C     DAMP = DAMPING FACTOR                                             GMA00500
C     SAMPT = SAMPLING TIME                                             GMA00510
```

```
C     TCX, TCY, TCZ = CONTROL TORQUE VALUES                                  GMA00520
C     ENERGY = TOTAL SYSTEM ENERGY                                           GMA00530
C     IMPLSE = IMPULSE INPUT FUNCTION                                        GMA00540
C     MIN = NUMBER OF MINUTES SYSTEM WILL BE OBSERVED                        GMA00550
C     SMODE = NUMBER OF STARTING MODE (INT)                                  GMA00560
C     MODE = NUMBER OF MODES (INT)                                           GMA00570
C     EMODE = NUMBER OF THE LAST MODE (INT)                                  GMA00580
C     NODE = NUMBER OF THE NOISE INPUT MODE (INT)                            GMA00590
C      *** NOISE SLOPE LOCATIONS IN DATA MATRIX ***                          GMA00600
C     ROWN1 = X-SLOPE LOCATION                                               GMA00610
C     ROWN2 = Y-SLOPE LOCATION                                               GMA00620
C     ROWN3 = Z-SLOPE LOCATION                                               GMA00630
C     C = OUTPUT MATRIX FOR Y                                                GMA00640
C     IDENT = IDENTITY MATRIX                                                GMA00650
C     RMN = MEASUREMENT NOISE COVARIANCE MATRIX                              GMA00660
C     QPN = PLANT NOISE COVARIANCE MATRIX                                    GMA00670
C     PNVARX = PLANT NOISE X-SLOPE VARIANCE                                  GMA00680
C     PNVARY = PLANT NOISE Y-SLOPE VARIANCE                                  GMA00690
C     PNVARZ = PLANT NOISE Z-SLOPE VARIANCE                                  GMA00700
C     MNVARX = MEASUREMENT NOISE X-SLOPE VARIANCE                            GMA00710
C     MNVARY = MEASUREMENT NOISE Y-SLOPE VARIANCE                            GMA00720
C     MNVARZ = MEASUREMENT NOISE Z-SLOPE VARIANCE                            GMA00730
C     ISEED = INITIALIZATION FOR RANDOM NUMBER GENERATOR                     GMA00740
C     XKAL = X MATRIX                                                        GMA00750
C     Y = OUTPUT MATRIX                                                      GMA00760
C     RNDM = RANDOM NUMBERS USED FOR WHITE NOISE IN MEASUREMENTS AND         GMA00770
C             IN PLANT FORCES                                                GMA00780
C     BN = B MATRIX TO MULTIPLY NOISE DISTURBANCES                           GMA00790
C     TNX,TNY,TNZ= NOISE TORQUES X,Y,Z SLOPES                                GMA00800
C     M2=2*MODE                                                              GMA00810
C                                                                            GMA00820
C                                                                            GMA00830
C                                                                            GMA00840
C     ************      SAMPLE OF SPACE EXEC FILE      **********************GMA00850
C                                                                            GMA00860
C     THIS FILE MUST BEGIN IN COLUMN 1 AND RUN WITH THE FOLLOWING            GMA00870
C     SEQUENCE FOR THE INITIAL RUN OF THE PROGRAM:                           GMA00880
C                                                                            GMA00890
C             FORTVS SPACE            (COMPILES PROGRAM)                     GMA00900
C             SPACE                   (EXECUTES EXEC FILE)                   GMA00910
C             LOAD SPACE (START       (LOADS AND EXECUTES PROGRAM)           GMA00920
C                                                                            GMA00930
C     SUBSEQUENT PROGRAM RUNS CAN ELIMINATE "FORTVS SPACE" IF NO             GMA00940
C     CHANGES HAVE BEEN MADE TO THE PROGRAM, AND CAN ELIMINATE               GMA00950
C     RUNNING THE EXEC FILE.                                                 GMA00960
C                                                                            GMA00970
C     FI 4 DISK THESIS INPUT B (PERM                                         GMA00980
C     FI 8 DISK UTILITY DATA  (RECFM VS BLOCK 133 PERM                       GMA00990
C     FI 11 DISK CNTRL OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM               GMA01000
C     FI 13 DISK GAMMA OUTPUT  (RECFM VS BLOCK 133 PERM                      GMA01010
C     FI 14 DISK MODE OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM                GMA01020
C     FI 16 DISK COST OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM                GMA01030
C     FI 17 DISK PRT  OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM                GMA01040
C     FI 18 DISK ERROR DATA   (RECFM F BLOCK 80 LRECL 80 PERM                GMA01050
C     FI 19 DISK END FILE   (RECFM F BLOCK 80 LRECL 80 PERM                  GMA01060
C     FI 20 DISK GMAT FILE (RECFM F BLOCK 80 LRECL 80 PERM                   GMA01070
```

```
C                                                                               GMA01080
C     ***************************************************************************GMA01090
C                                                                               GMA01100
      PARAMETER (JR=5243, KR=5397, MR=262139)                                   GMA01110
C                                                                               GMA01120
      MIN =1200.0                                                               GMA01130
      WT=1.0D00                                                                 GMA01140
      PI = 4.0D0 * ATAN(1.0D0)                                                  GMA01150
C                                                                               GMA01160
C     ***************************************************************************GMA01170
C     *****          READ LAMA AND UGVEX MATRICIES          *****               GMA01180
C     ***************************************************************************GMA01190
C                                                                               GMA01200
      CALL EXCMS ('CLRSCRN')                                                    GMA01210
      WRITE(6,1008)                                                             GMA01220
      WRITE(6,*) '                    READING LAMA AND UGVEX MATRICIES'         GMA01230
      WRITE(6,*) ' '                                                            GMA01240
C     THIS SECTION READS THE LAMA VECTOR AND THE UGVEX                          GMA01250
C     MATRIX AND STORES THEM IN MEMORY FOR FURTHER RECALL OF                    GMA01260
C     DESIRED LOCATION DATA.                                                    GMA01270
C                                                                               GMA01280
      READ(4,1001) NAM                                                          GMA01290
      READ(4,1002)(LAMA(I),I=1,100)                                             GMA01300
      READ(4,1001) NAM                                                          GMA01310
      DO 5 J = 1,100                                                            GMA01320
         READ(4,1002)(UGVEX(I,J),I=1,684)                                       GMA01330
5     CONTINUE                                                                  GMA01340
C                                                                               GMA01350
1001  FORMAT(1X,A6)                                                             GMA01360
1002  FORMAT(1X,8E15.8)                                                         GMA01370
1008  FORMAT(1X,////)                                                           GMA01380
C                                                                               GMA01390
500   CALL EXCMS ('CLRSCRN')                                                    GMA01400
C                                                                               GMA01410
C     ***************       STARTING MODE NUMBER      ******************        GMA01420
C     ** SMODE 7 TO 100 (INTEGER) *****                                         GMA01430
      SMODE=10                                                                  GMA01440
C                                                                               GMA01450
      WRITE (16,700) SMODE                                                      GMA01460
700   FORMAT (' ','STARTING MODE NUMBER:  ',I2)                                 GMA01470
C                                                                               GMA01480
C     ********************    NUMBER OF MODES TO SCAN    ***************        GMA01490
C     ** MODE 1 TO 93 (INTEGER)                                                 GMA01500
C                                                                               GMA01510
      MODE= 3                                                                   GMA01520
C                                                                               GMA01530
      EMODE = SMODE + MODE - 1                                                  GMA01540
C                                                                               GMA01550
      WRITE (16,701) MODE                                                       GMA01560
701   FORMAT (' ','NUMBER OF MODES SCANNED:  ',I2)                              GMA01570
C                                                                               GMA01580
C     ***************    NOISE INPUT POSITION      ********************        GMA01590
C     ** NODE 1 TO 114 (INTEGER) (IF 0 THEN NO NOISE INPUT)                     GMA01600
      NODE= 8                                                                   GMA01610
C                                                                               GMA01620
```

```
      WRITE (16,702) NODE                                                GMA01630
702   FORMAT (' ',' NOISE NODE LOCATION:    ',I5)                        GMA01640
C                                                                        GMA01650
C                                                                        GMA01660
C     ***************          SAMPLING TIME          ***************    GMA01670
C     ** SAMPT MUST BE LESS THAN OR EQUAL TO SAMPTM **                   GMA01680
      SAMPT = .05                                                        GMA01690
         SAMPTM = ((2.0D0*PI)/SQRT(LAMA(EMODE)))/2.0D0                   GMA01700
         IF (SAMPT.GE.SAMPTM) THEN                                       GMA01710
              SAMPT=SAMPTM                                               GMA01720
         ENDIF                                                           GMA01730
C                                                                        GMA01740
      WRITE (16,900) MIN                                                 GMA01750
900   FORMAT (' ',2X,'MIN:   ',F8.3)                                     GMA01760
C                                                                        GMA01770
      WRITE (16,703) SAMPT                                               GMA01780
703   FORMAT (' ','SAMPLING TIME:   ',D12.4)                             GMA01790
C                                                                        GMA01800
C     ******************         DAMPING FACTOR         ****************  GMA01810
C     ** DAMP 0.0 TO 1.0 (REAL*8)                                        GMA01820
      DAMP=.01                                                           GMA01830
C                                                                        GMA01840
      WRITE (16,704) DAMP                                                GMA01850
704   FORMAT (' ','DAMPING FACTOR:   ',D12.4)                            GMA01860
C                                                                        GMA01870
C                                                                        GMA01880
C     *** PLANT NOISE VARIANCE ***                                       GMA01890
C     ** PNVARX, PNVARY, PNVARZ GT 0.0                                   GMA01900
C                                                                        GMA01910
      SF1=2.5D06                                                         GMA01920
C                                                                        GMA01930
      PNVARX=1.0D00*SF1                                                  GMA01940
      PNVARY=1.0D00*SF1                                                  GMA01950
      PNVARZ=1.0D00*SF1                                                  GMA01960
C                                                                        GMA01970
C                                                                        GMA01980
C                                                                        GMA01990
C     *** MEASUREMENT NOISE VARIANCE ***                                 GMA02000
C     ** MNVARX, MNVARY, MNVARZ GT 0.0                                   GMA02010
      SF=1.0                                                             GMA02020
      MNVX1=5.5D-03*SF                                                   GMA02030
      MNVY1=5.5D-03*SF                                                   GMA02040
      MNVZ1=5.5D-03*SF                                                   GMA02050
C                                                                        GMA02060
510   CALL EXCMS ('CLRSCRN')                                             GMA02070
      WRITE (6,1008)                                                     GMA02080
      WRITE (6,*) '                                PROGRAM RUNNING'      GMA02090
C                                                                        GMA02100
C     **************       NOISE INPUT LOCATION       ***************    GMA02110
C                                                                        GMA02120
      ROWN3 = NODE*6                                                     GMA02130
      ROWN2 = (NODE*6) - 1                                               GMA02140
      ROWN1 = (NODE*6) - 2                                               GMA02150
      COUNT = 0                                                          GMA02160
C                                                                        GMA02170
```

```
C     ************       INITIALIZE MATRICIES       ******************        GMA02180
C                                                                              GMA02190
      DO 40 I = 1,3                                                            GMA02200
         DO 45 J = 1,3                                                         GMA02210
             RMN(I,J)=0.0                                                      GMA02220
45       CONTINUE                                                              GMA02230
40    CONTINUE                                                                 GMA02240
C                                                                              GMA02250
      DO 47 I=1,50                                                             GMA02260
         DO 46 J=1,50                                                          GMA02270
         IDENT(I,J)=0.0                                                        GMA02280
         PK(I,J)=0.0                                                           GMA02290
46       CONTINUE                                                              GMA02300
47    CONTINUE                                                                 GMA02310
C                                                                              GMA02320
      DO 48 K=1,50                                                             GMA02330
         IDENT(K,K)=1.0                                                        GMA02340
48    CONTINUE                                                                 GMA02350
C                                                                              GMA02360
C     *** INITIALIZE RMN AND QPN MATRICES ***                                  GMA02370
C                                                                              GMA02380
      DO 60 I=1,3                                                              GMA02390
         DO 58 J=1,3                                                           GMA02400
         QPN(I,J)=0.0                                                          GMA02410
58       CONTINUE                                                              GMA02420
60    CONTINUE                                                                 GMA02430
C                                                                              GMA02440
      RMN(1,1)=MNVX1**2                                                        GMA02450
      RMN(2,2)=MNVY1**2                                                        GMA02460
      RMN(3,3)=MNVZ1**2                                                        GMA02470
      QPN(1,1)=PNVARX**2.0                                                     GMA02480
      QPN(2,2)=PNVARY**2.0                                                     GMA02490
      QPN(3,3)=PNVARZ**2.0                                                     GMA02500
C                                                                              GMA02510
9999  FORMAT (' ','   ')                                                       GMA02520
C     ********************************************************************     GMA02530
C     ******              BEGIN MAIN PROGRAM                        ******     GMA02540
C     ********************************************************************     GMA02550
C                                                                              GMA02560
      CALL STMTRX(EMODE,SMODE,SAMPT,DAMP,PHI,GAMMA,A,B,LAMA,UGVEX,C,          GMA02570
     +   ROWN1,ROWN2,ROWN3,BN)                                                 GMA02580
C                                                                              GMA02590
C                                                                              GMA02600
C     *** PRE-LOOP PORTION OF KALMAN FILTER                                    GMA02610
      JK=SMODE*2-2                                                             GMA02620
      M2=2*MODE                                                                GMA02630
      DO 94 I=1,3                                                              GMA02640
         DO 92 J=1,M2                                                          GMA02650
         JL=JK+J                                                               GMA02660
         SUM=0.0                                                               GMA02670
              DO 90 K=1,3                                                      GMA02680
              SUM=SUM+QPN(I,K)*BN(JL,K)                                        GMA02690
90            CONTINUE                                                         GMA02700
         TMP1(J,I)=SUM                                                         GMA02710
92       CONTINUE                                                              GMA02720
94    CONTINUE                                                                 GMA02730
```

```
C                                                                       GMA02740
C                                                                       GMA02750
      DO 98 I=1,M2                                                      GMA02760
      JL=JK+I                                                           GMA02770
         DO 97 J=1,M2                                                   GMA02780
         SUM=0.0                                                        GMA02790
              DO 96 K=1,3                                               GMA02800
              SUM=SUM+BN(JL,K)*TMP1(J,K)                                GMA02810
96            CONTINUE                                                  GMA02820
         BQBT(I,J)=SUM                                                  GMA02830
97       CONTINUE                                                       GMA02840
98    CONTINUE                                                          GMA02850
C                                                                       GMA02860
      M2=2*MODE                                                         GMA02870
      DO 100 I=1,M2                                                     GMA02880
         DO 99 J=1,M2                                                   GMA02890
         TMP3(I,J)=0.0                                                  GMA02900
99       CONTINUE                                                       GMA02910
100   CONTINUE                                                          GMA02920
      JL=JK+M2                                                          GMA02930
      DO 9375 I=1,3                                                     GMA02940
         DO 9374 J=1,JL                                                 GMA02950
         C(I,J)=C(I,J)*SF                                               GMA02960
9374     CONTINUE                                                       GMA02970
9375  CONTINUE                                                          GMA02980
C                                                                       GMA02990
C     ************************************************************      GMA03000
C     ******     THIS SECTION COMPUTES THE STATE UPDATE     ******      GMA03010
C     ************************************************************      GMA03020
      ESUM=0.0                                                          GMA03030
      COUNT = 0                                                         GMA03040
      ENERGY = 0.0D0                                                    GMA03050
      TIME = 0.0                                                        GMA03060
      CGN=0.0                                                           GMA03070
C     ******  SETS LOOP FOR THE ITERATIONS NECESSARY TO OBSERVE  ******  GMA03080
C     ******  THE SYSTEM FOR THE NUMBER OF MINUTES SPECIFIED     ******  GMA03090
C                                                                       GMA03100
      LOOP = INT((MIN*60.0)/SAMPT)                                      GMA03110
      PRT=(DBLE(LOOP))/1200.0                                           GMA03120
      PRTA=(DBLE(LOOP))/2400.0                                          GMA03130
      CNTA=0.0                                                          GMA03140
      ACHK=1.0D-10                                                      GMA03150
      H1=0.0                                                            GMA03160
      H2=0.0                                                            GMA03170
      H3=0.0                                                            GMA03180
      H4=0.0                                                            GMA03190
      H5=0.0                                                            GMA03200
      H6=0.0                                                            GMA03210
      TCHK=MIN*60.0                                                     GMA03220
9991  CONTINUE                                                          GMA03230
C                                                                       GMA03240
         TIME = TIME+   SAMPT                                           GMA03250
C                                                                       GMA03260
      CGN=CGN+1.0                                                       GMA03270
C     CNTA=CNTA+1.0                                                     GMA03280
```

```
C     *** START OF KALMAN FILTER ***                                    GMA03290
C                                                                       GMA03300
      M2=2*MODE                                                         GMA03310
C                                                                       GMA03320
C     *** COMPUTATION OF PK*AT ***                                      GMA03330
C                                                                       GMA03340
      JK=2*SMODE-2                                                      GMA03350
      DO 175 I=1,M2                                                     GMA03360
         DO 170 J=1,M2                                                  GMA03370
         JL=JK+J                                                        GMA03380
         SUM=0.0                                                        GMA03390
              DO 165 K=1,M2                                             GMA03400
              JM=JK+K                                                   GMA03410
              SUM =SUM+PK(I,K)*A(JL,JM)                                 GMA03420
165           CONTINUE                                                  GMA03430
         TMP3(I,J)=SUM                                                  GMA03440
170      CONTINUE                                                       GMA03450
175   CONTINUE                                                          GMA03460
C                                                                       GMA03470
C                                                                       GMA03480
C     *** COMPUTATION OF A*(PK*AT)+ BQBT = PK1 ***                      GMA03490
C                                                                       GMA03500
      DO 190 I=1,M2                                                     GMA03510
      JL=JK+I                                                           GMA03520
         DO 185 J=1,M2                                                  GMA03530
         SUM=0.0                                                        GMA03540
              DO 180 K=1,M2                                             GMA03550
              JM=JK+K                                                   GMA03560
              SUM=SUM+A(JL,JM)*TMP3(K,J)                                GMA03570
180           CONTINUE                                                  GMA03580
         PK1(I,J)=SUM+BQBT(I,J)                                         GMA03590
185      CONTINUE                                                       GMA03600
190   CONTINUE                                                          GMA03610
C     **********                                                        GMA03620
C                                                                       GMA03630
C     *** COMPUTE PK1*CT *****                                          GMA03640
C                                                                       GMA03650
      DO 205 I=1,M2                                                     GMA03660
         DO 200 J=1,3                                                   GMA03670
         SUM=0.0                                                        GMA03680
              DO 195 K=1,M2                                             GMA03690
              JM=JK+K                                                   GMA03700
              SUM=SUM+PK1(I,K)*C(J,JM)                                  GMA03710
195           CONTINUE                                                  GMA03720
         TMP1(I,J)=SUM                                                  GMA03730
200      CONTINUE                                                       GMA03740
205   CONTINUE                                                          GMA03750
C     **********                                                        GMA03760
C                                                                       GMA03770
C     *** COMPUTE C*(PK1*CT)+RMN ***                                    GMA03780
      DO 220 I=1,3                                                      GMA03790
         DO 215 J=1,3                                                   GMA03800
         SUM=0.0                                                        GMA03810
              DO 210 K=1,M2                                             GMA03820
              JM=JK+K                                                   GMA03830
```

```
                SUM=SUM+C(I,JM)*TMP1(K,J)                                GMA03840
210             CONTINUE                                                 GMA03850
           TMP2(I,J)=SUM+RMN(I,J)                                        GMA03860
215        CONTINUE                                                      GMA03870
220     CONTINUE                                                         GMA03880
C                                                                        GMA03890
C       *** COMPUTATION OF THE INVERSE OF C*PK1*CT + R                   GMA03900
C                                                                        GMA03910
C                                                                        GMA03920
        CALL DLINRG ( 3,TMP2,3,TMP2,3)                                   GMA03930
C                                                                        GMA03940
C       *** COMPUTE CT*INV(C*PK1*CT+R)                                   GMA03950
C                                                                        GMA03960
        DO 245 I=1,M2                                                    GMA03970
        JL=JK+I                                                          GMA03980
           DO 240 J=1,3                                                  GMA03990
           SUM=0.0                                                       GMA04000
                DO 235 K=1,3                                             GMA04010
                SUM=SUM+C(K,JL)*TMP2(K,J)                                GMA04020
235             CONTINUE                                                 GMA04030
           TMP1(I,J)=SUM                                                 GMA04040
240        CONTINUE                                                      GMA04050
245     CONTINUE                                                         GMA04060
C       ****************                                                 GMA04070
C                                                                        GMA04080
C       *** COMPUTE PK1*C*INV(C*PK1*CT+R) = G ******                     GMA04090
C                                                                        GMA04100
        DO 260 I=1,M2                                                    GMA04110
           DO 255 J=1,3                                                  GMA04120
           SUM=0.0                                                       GMA04130
                DO 250 K=1,M2                                            GMA04140
                SUM=SUM+PK1(I,K)*TMP1(K,J)                               GMA04150
250             CONTINUE                                                 GMA04160
           G(I,J)=SUM                                                    GMA04170
255        CONTINUE                                                      GMA04180
260     CONTINUE                                                         GMA04190
C                                                                        GMA04200
        N9=DABS((G(1,1)-H1)/G(1,1))                                      GMA04210
        IF (N9.GT.ACHK)      THEN                                        GMA04220
        GO TO 7377                                                       GMA04230
        END IF                                                           GMA04240
        N9=DABS((G(1,3)-H2)/G(1,3))                                      GMA04250
        IF (N9.GT.ACHK)THEN                                              GMA04260
        GO TO 7377                                                       GMA04270
        END IF                                                           GMA04280
        N9=DABS((G(2,1)-H3)/G(2,1))                                      GMA04290
        IF (N9.GT.ACHK)      THEN                                        GMA04300
        GO TO 7377                                                       GMA04310
        END IF                                                           GMA04320
        N9=DABS((G(2,3)-H4)/G(2,3))                                      GMA04330
        IF (N9.GT.ACHK)      THEN                                        GMA04340
        GO TO 7377                                                       GMA04350
        END IF                                                           GMA04360
        N9=DABS((G(3,3)-H5)/G(3,3))                                      GMA04370
        IF (N9.GT.ACHK)      THEN                                        GMA04380
        GO TO 7377                                                       GMA04390
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      END IF                                                          GMA04400
      N9=DABS((G(M2,3)-H6)/G(M2,3))                                   GMA04410
      IF (N9.GT.ACHK)     THEN                                        GMA04420
      GO TO 7377                                                      GMA04430
      END IF                                                          GMA04440
      GO TO 400                                                       GMA04450
C                                                                     GMA04460
C                                                                     GMA04470
7377  CONTINUE                                                        GMA04480
      H1=G(1,1)                                                       GMA04490
      H2=G(1,3)                                                       GMA04500
      H3=G(2,1)                                                       GMA04510
      H4=G(2,3)                                                       GMA04520
      H5=G(3,3)                                                       GMA04530
      H6=G(M2,3)                                                      GMA04540
                                                                      GMA04550
                                                                      GMA04560
                                                                      GMA04570
      IF (TCHK.LE.TIME) THEN                                          GMA04580
      GO TO 400                                                       GMA04590
      END IF                                                          GMA04600
      IF (CGN.GE.PRT)   THEN                                          GMA04610
C                                                                     GMA04620
      WRITE (6,*) 'TIME= ', TIME, ' SEC.'                             GMA04630
C                                                                     GMA04640
      WRITE (6,*) 'N9= ', N9                                          GMA04650
      CGN=0.0                                                         GMA04660
      END IF                                                          GMA04670
C                                                                     GMA04680
C     *** COMPUTE IDENT  - G*C                                        GMA04690
C                                                                     GMA04700
      DO 275 I=1,M2                                                   GMA04710
         DO 270 J=1,M2                                                GMA04720
         JL=JK+J                                                      GMA04730
         SUM=0.0                                                      GMA04740
              DO 265 K=1,3                                            GMA04750
              SUM=SUM+G(I,K)*C(K,JL)                                  GMA04760
265           CONTINUE                                                GMA04770
         TMP3(I,J)= IDENT(I,J)-SUM                                    GMA04780
270      CONTINUE                                                     GMA04790
275   CONTINUE                                                        GMA04800
C     ************************                                        GMA04810
C                                                                     GMA04820
C     *** COMPUTE PK= (INDENT - G*C)*PK1                              GMA04830
C                                                                     GMA04840
      DO 290 I=1,M2                                                   GMA04850
         DO 285 J=1,M2                                                GMA04860
         SUM=0.0                                                      GMA04870
              DO 280 K=1,M2                                           GMA04880
              SUM=SUM+TMP3(I,K)*PK1(K,J)                              GMA04890
280           CONTINUE                                                GMA04900
         PK(I,J)=SUM                                                  GMA04910
285      CONTINUE                                                     GMA04920
290   CONTINUE                                                        GMA04930
C     **********************                                          GMA04940
C                                                                     GMA04950
```

```
C     END OF KALMAN FILTER PART 1 - START OF PART 2 *****                    GMA04960
C                                                                            GMA04970
C                                                                            GMA04980
C                                                                            GMA04990
      GO TO 9991                                                             GMA05000
C                                                                            GMA05010
400   CONTINUE                                                               GMA05020
C                                                                            GMA05030
      WRITE (20,1008)                                                        GMA05040
      WRITE (20,*) 'TIME= ',TIME                                             GMA05050
      DO 384 I=1,M2                                                          GMA05060
      WRITE (20,5350)   G(I,1),G(I,2),G(I,3)                                 GMA05070
384   CONTINUE                                                               GMA05080
5350  FORMAT (' ',5X,D15.8 ,5X,D15.8 ,5X,D15.8 )                             GMA05090
      WRITE (20,*) 'N9= ',N9                                                 GMA05100
C                                                                            GMA05110
C     *** COMPUTE AGC = A - G*C                                              GMA05120
C                                                                            GMA05130
      M2=2*MODE                                                              GMA05140
      JK=2*SMODE-2                                                           GMA05150
C                                                                            GMA05160
      DO 7155 I=1,M2                                                         GMA05170
      JL=JK+I                                                                GMA05180
         DO 7154 J=1,M2                                                      GMA05190
         JM=JK+J                                                             GMA05200
         SUM=0.0                                                             GMA05210
              DO 7153 K=1,3                                                  GMA05220
              SUM=SUM+G(I,K)*C(K,JM)                                         GMA05230
7153          CONTINUE                                                       GMA05240
         AGC(I,J)=A(JL,JM)-SUM                                               GMA05250
7154     CONTINUE                                                            GMA05260
7155  CONTINUE                                                               GMA05270
C                                                                            GMA05280
C                                                                            GMA05290
C                                                                            GMA05300
C     *** COMPUTE THE EIGENVALUES OF AGC                                     GMA05310
C                                                                            GMA05320
      CALL DEVCRG (M2, AGC, 100, EVAL, EVEC, 100)                            GMA05330
C                                                                            GMA05340
C     **** PRINT EVAL (EIGENVALUE) MATRIX                                    GMA05350
C                                                                            GMA05360
      DO 7157 I=1,M2                                                         GMA05370
      WRITE (20,*) 'I= ', I, 'EIG= ', EVAL(I)                                GMA05380
7157  CONTINUE                                                               GMA05390
C                                                                            GMA05400
C                                                                            GMA05410
C                                                                            GMA05420
599   STOP                                                                   GMA05430
      END                                                                    GMA05440
C                                                                            GMA05450
C                                                                            GMA05460
C                                                                            GMA05470
C                                                                            GMA05480
C                                                                            GMA05490
C     ********************************************************************** GMA05500
C     THIS SUBROUTINE COMPUTES THE STATE TRANSITION MATRIX FOR EACH          GMA05510
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C     OF THE 100 MODES                                                          GMA05520
C     ************************************************************************* GMA05530
C                                                                               GMA05540
      SUBROUTINE STMTRX(EMODE,SMODE,T,D,PHI,GAMMA,A,B,LAMA,UGVEX,C,             GMA05550
     +        ROWN1,ROWN2,ROWN3,BN)                                             GMA05560
C                                                                               GMA05570
      REAL*8 WN,GMA,PHI(2,2,100),GAMMA(2,100),EGT,T,COSW1T,SINW1T               GMA05580
      REAL*8 W1,D,A(200,200),B(200,3),C(6,200),BN(200,3)                        GMA05590
      REAL LAMA(100),UGVEX(684,100)                                             GMA05600
      INTEGER SMODE,R,EMODE,JJ,KK,ROWN1,ROWN2,ROWN3                             GMA05610
C                                                                               GMA05620
C                                                                               GMA05630
C                                                                               GMA05640
C                                                                               GMA05650
C                                                                               GMA05660
      DO 600 I = 1    ,100                                                      GMA05670
         WN = DBLE(SQRT(LAMA(I)))                                               GMA05680
         GMA = D*WN/2.0                                                         GMA05690
         EGT = DEXP(-GMA*T)                                                     GMA05700
         W1 = DSQRT((WN**2)-(GMA**2))                                           GMA05710
         COSW1T = DCOS(W1*T)                                                    GMA05720
         SINW1T = DSIN(W1*T)                                                    GMA05730
C                                                                               GMA05740
C                                                                               GMA05750
C                                                                               GMA05760
C                                                                               GMA05770
C                                                                               GMA05780
         IF(WN.EQ.0)THEN                                                        GMA05790
              PHI(1,1,I) = EGT*COSW1T                                           GMA05800
              PHI(1,2,I) = T                                                    GMA05810
              PHI(2,1,I) = 0                                                    GMA05820
              PHI(2,2,I) = EGT*COSW1T                                           GMA05830
C                                                                               GMA05840
C                                                                               GMA05850
C                                                                               GMA05860
C                                                                               GMA05870
C                                                                               GMA05880
C                                                                               GMA05890
              GAMMA(1,I) = 0                                                    GMA05900
              GAMMA(2,I) = 0                                                    GMA05910
         ELSE                                                                   GMA05920
C                                                                               GMA05930
C                                                                               GMA05940
C                                                                               GMA05950
C                                                                               GMA05960
C                                                                               GMA05970
         PHI(1,1,I) = EGT*(COSW1T + (GMA*(W1**(-1)))*SINW1T)                    GMA05980
         PHI(1,2,I) = (W1**(-1))*EGT*SINW1T                                     GMA05990
         PHI(2,1,I) = -(WN**2)*(W1**(-1))*EGT*SINW1T                            GMA06000
         PHI(2,2,I) = EGT*(COSW1T - (GMA*(W1**(-1)))*SINW1T)                    GMA06010
C                                                                               GMA06020
C                                                                               GMA06030
C                                                                               GMA06040
C                                                                               GMA06050
      GAMMA(1,I)=(WN**(-2))*(1.D0-EGT*COSW1T-EGT*(GMA/W1)*SINW1T)               GMA06060
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```
         GAMMA(2,I) = (W1**(-1))*EGT*SINW1T                              GMA06070
C                                                                        GMA06080
C                                                                        GMA06090
C                                                                        GMA06100
C                                                                        GMA06110
         ENDIF                                                           GMA06120
C                                                                        GMA06130
C                                                                        GMA06140
C                                                                        GMA06150
600   CONTINUE                                                           GMA06160
C                                                                        GMA06170
C                                                                        GMA06180
C                                                                        GMA06190
C                                                                        GMA06200
      R = 1                                                              GMA06210
C                                                                        GMA06220
      DO 610 K = 1    ,100                                               GMA06230
C                                                                        GMA06240
C                                                                        GMA06250
C                                                                        GMA06260
C                                                                        GMA06270
C                                                                        GMA06280
         A(R,R) = PHI(1,1,K)                                             GMA06290
         A(R,R+1) = PHI(1,2,K)                                           GMA06300
         A(R+1,R) = PHI(2,1,K)                                           GMA06310
         A(R+1,R+1) = PHI(2,2,K)                                         GMA06320
C                                                                        GMA06330
C                                                                        GMA06340
C                                                                        GMA06350
C                                                                        GMA06360
C                                                                        GMA06370
C     *** B MATRIX FOR MULTIPLYING CONTROL TORQUES                       GMA06380
C                                                                        GMA06390
         B(R,1) = GAMMA(1,K)*DBLE(UGVEX(412,K))                          GMA06400
         B(R,2) = GAMMA(1,K)*DBLE(UGVEX(413,K))                          GMA06410
         B(R,3) = GAMMA(1,K)*DBLE(UGVEX(414,K))                          GMA06420
         B(R+1,1) = GAMMA(2,K)*DBLE(UGVEX(412,K))                        GMA06430
         B(R+1,2) = GAMMA(2,K)*DBLE(UGVEX(413,K))                        GMA06440
         B(R+1,3) = GAMMA(2,K)*DBLE(UGVEX(414,K))                        GMA06450
C                                                                        GMA06460
C                                                                        GMA06470
C                                                                        GMA06480
C                                                                        GMA06490
C                                                                        GMA06500
C                                                                        GMA06510
C                                                                        GMA06520
C     *** BN MATRIX FOR MULTIPLYING THE NOISE DISTURBANCES               GMA06530
C                                                                        GMA06540
C                                                                        GMA06550
C                                                                        GMA06560
C                                                                        GMA06570
      BN(R,1)=GAMMA(1,K)*DBLE(UGVEX(ROWN1,K))                            GMA06580
      BN(R,2)=GAMMA(1,K)*DBLE(UGVEX(ROWN2,K))                            GMA06590
      BN(R,3)=GAMMA(1,K)*DBLE(UGVEX(ROWN3,K))                            GMA06600
      BN(R+1,1)=GAMMA(2,K)*DBLE(UGVEX(ROWN1,K))                          GMA06610
      BN(R+1,2)=GAMMA(2,K)*DBLE(UGVEX(ROWN2,K))                          GMA06620
```

```
      BN(R+1,3)=GAMMA(2,K)*DBLE(UGVEX(ROWN3,K))                          GMA06630
C                                                                        GMA06640
C                                                                        GMA06650
C                                                                        GMA06660
C                                                                        GMA06670
C                                                                        GMA06680
C                                                                        GMA06690
         R = R+2                                                         GMA06700
610   CONTINUE                                                           GMA06710
C                                                                        GMA06720
C                                                                        GMA06730
C                                                                        GMA06740
C                                                                        GMA06750
C                                                                        GMA06760
C                                                                        GMA06770
C                                                                        GMA06780
C     *** C MATRIX PRODUCTION ***                                        GMA06790
C                                                                        GMA06800
C                                                                        GMA06810
C                                                                        GMA06820
      JJ=-1                                                              GMA06830
      DO 640 I=1,100                                                     GMA06840
      JJ=JJ+1                                                            GMA06850
      KK=I+JJ                                                            GMA06860
C                                                                        GMA06870
C                                                                        GMA06880
      C(1,KK) = DBLE(UGVEX(418,I))                                       GMA06890
      C(2,KK) = DBLE(UGVEX(419,I))                                       GMA06900
      C(3,KK) = DBLE(UGVEX(420,I))                                       GMA06910
C                                                                        GMA06920
C                                                                        GMA06930
C                                                                        GMA06940
      KK=KK+1                                                            GMA06950
C                                                                        GMA06960
      C(1,KK)=0.0                                                        GMA06970
      C(2,KK)=0.0                                                        GMA06980
      C(3,KK)=0.0                                                        GMA06990
C                                                                        GMA07000
640   CONTINUE                                                           GMA07010
C                                                                        GMA07020
C                                                                        GMA07030
C                                                                        GMA07040
      RETURN                                                             GMA07050
      END                                                                GMA07060
```

APPENDIX B. KALMAN OBSERVER AND PLANT SIMULATION

```
C                                                                       SIM00010
C     ***************************************************************** SIM00020
C     ******                    SIMRUN                           ****** SIM00030
C     ******  ADAPTED TO READ KALMAN FILETER G MATRICE            ****** SIM00040
C     ******  THEN RUN ALL N   MODES OF THE PLANT WHILE           ****** SIM00050
C     ******  USING A KALMAN FILTER TO OBSERVE M                  ****** SIM00060
C     ******  NUMBER OF STATES                                    ****** SIM00070
C     ***************************************************************** SIM00080
C                                                                       SIM00090
C                                                                       SIM00100
C     ***************************************************************** SIM00110
C     ******              VARIABLE DECLARATIONS                  ****** SIM00120
C     ***************************************************************** SIM00130
C                                                                       SIM00140
      EXTERNAL STMTRX,EXCMS                                             SIM00150
      CHARACTER*6 NAM                                                   SIM00160
      CHARACTER*1 AGAIN,CORECT,RAGAIN                                   SIM00170
      INTEGER ROWN1,ROWN2,ROWN3,COUNT,NODE,MODE,KQ,EMODE,SMODE,R2M,C2M  SIM00180
      INTEGER CT,CF,KADJ,CFADJ,LOOP,PRNT,JJ,JK,N1,JR,KR,MR,ISEED,M2     SIM00190
      INTEGER ITYPE(200), IPVT(100), NS, NF, SN, FN                     SIM00200
      INTEGER JL,J1,JM , JP, JQ, KA, KB, KC, KD, KE, KF, KG             SIM00210
C                                                                       SIM00220
C                                                                       SIM00230
C                                                                       SIM00240
      REAL LAMA(100), UGVEX(684,100),RNODE,RMODE,MIN                    SIM00250
      REAL*8 PHI(2,2,100),GAMMA(2,100),EGT,GMA,WN,W1,X1T,X2T,TIME       SIM00260
      REAL*8 A(200,200),B(200,3),F(3, 50),IMPLSE,ENERGY                 SIM00270
      REAL*8 COSW1T,SINW1T,X(200)                                       SIM00280
      REAL*8 TCX,TCY,TCZ,DAMP,SAMPT,PI,SAMPTM,SUM1,SUM2,SUM3,SUMC       SIM00290
      REAL*8 C(3,200), IDENT( 50, 50), RMN(3,3), QPN(3,3)               SIM00300
      REAL*8 Y(3)  , BN(200,3)                                          SIM00310
      REAL*8 PNVARX, PNVARY, PNVARZ                                     SIM00320
      REAL*8 MNVARX, MNVARY, MNVARZ                                     SIM00330
      REAL*8 SUM, RNDM(6), RND1, RND2                                   SIM00340
      REAL*8 XH( 50)  ,BQBT( 50, 50)                                    SIM00350
      REAL*8 SF1                                                        SIM00360
      REAL*8 TMP1( 50,3), TMP2(3,3), TMP3( 50, 50)                      SIM00370
      REAL*8 G( 50,3)                                                   SIM00380
      REAL*8 XH1( 50)  ,DY(3)  , ES,ED,ESUM,CGN,PRT                     SIM00390
      REAL*8 WT , WD(3), BNWD(200)                                      SIM00400
      REAL*8 AX(200) , V(3), SF , TO, CTT, ESS                          SIM00410
      REAL*8 CTG, XDEL, E2(100), XDEL1, ERS, PRT1, E3(100), XS(100)     SIM00420
C                                                                       SIM00430
C     ***************************************************************** SIM00440
C     ******              VARIABLE DEFINITIONS                   ****** SIM00450
C     ***************************************************************** SIM00460
C                                                                       SIM00470
C     STMTRX = SUBROUTINE EXTABLISHES STATE TRANSITION MATRICIES        SIM00480
C     LAMA = VECTOR OF THE SQUARE OF THE NATURAL FREQUENCIES            SIM00490
C     UGVEX = MODE POSITONS AND SLOPES OF THE NODAL POINTS              SIM00500
C     PHI = STATE TRANSITION MATRICIES FOR EACH MODE                    SIM00510
```

```
C     GAMMA = INPUT TRANSITION MATRIX                                    SIM00520
C     A = DIAGONAL MATRIX CONSISTING OF PHI                              SIM00530
C     B = INPUT MATRIX OF GAMMA AND CONTROL SLOPES                       SIM00540
C     DAMP = DAMPING FACTOR                                              SIM00550
C     SAMPT = SAMPLING TIME                                              SIM00560
C     TCX, TCY, TCZ = CONTROL TORQUE VALUES                              SIM00570
C     ENERGY = TOTAL SYSTEM ENERGY                                       SIM00580
C     IMPLSE = IMPULSE INPUT FUNCTION                                    SIM00590
C     MIN = NUMBER OF MINUTES SYSTEM WILL BE OBSERVED                    SIM00600
C     SMODE = NUMBER OF STARTING MODE (INT)                              SIM00610
C     MODE = NUMBER OF MODES (INT)                                       SIM00620
C     EMODE = NUMBER OF THE LAST MODE (INT)                              SIM00630
C     NODE = NUMBER OF THE NOISE INPUT MODE (INT)                        SIM00640
C      **** NOISE SLOPE LOCATIONS IN DATA MATRIX ***                     SIM00650
C     ROWN1 = X-SLOPE LOCATION                                           SIM00660
C     ROWN2 = Y-SLOPE LOCATION                                           SIM00670
C     ROWN3 = Z-SLOPE LOCATION                                           SIM00680
C     C = OUTPUT MATRIX FOR Y                                            SIM00690
C     IDENT = IDENTITY MATRIX                                            SIM00700
C     RMN = MEASUREMENT NOISE COVARIANCE MATRIX                          SIM00710
C     QPN = PLANT NOISE COVARIANCE MATRIX                                SIM00720
C     PNVARX = PLANT NOISE X-SLOPE VARIANCE                              SIM00730
C     PNVARY = PLANT NOISE Y-SLOPE VARIANCE                              SIM00740
C     PNVARZ = PLANT NOISE Z-SLOPE VARIANCE                              SIM00750
C     MNVARX = MEASUREMENT NOISE X-SLOPE VARIANCE                        SIM00760
C     MNVARY = MEASUREMENT NOISE Y-SLOPE VARIANCE                        SIM00770
C     MNVARZ = MEASUREMENT NOISE Z-SLOPE VARIANCE                        SIM00780
C     ISEED = INITIALIZATION FOR RANDOM NUMBER GENERATOR                 SIM00790
C     XKAL = X MATRIX                                                    SIM00800
C     Y = OUTPUT MATRIX                                                  SIM00810
C     RNDM = RANDOM NUMBERS USED FOR WHITE NOISE IN MEASUREMENTS AND     SIM00820
C              IN PLANT FORCES                                           SIM00830
C     BN = B MATRIX TO MULTIPLY NOISE DISTURBANCES                       SIM00840
C     TNX,TNY,TNZ= NOISE TORQUES X,Y,Z SLOPES                            SIM00850
C     M2=2*MODE                                                          SIM00860
C                                                                        SIM00870
C                                                                        SIM00880
C                                                                        SIM00890
C     ************      SAMPLE OF SPACE EXEC FILE      ********************** SIM00900
C                                                                        SIM00910
C     THIS FILE MUST BEGIN IN COLUMN 1 AND RUN WITH THE FOLLOWING        SIM00920
C     SEQUENCE FOR THE INITIAL RUN OF THE PROGRAM:                       SIM00930
C                                                                        SIM00940
C             FORTVS SPACE            (COMPILES PROGRAM)                 SIM00950
C             SPACE                   (EXECUTES EXEC FILE)               SIM00960
C             LOAD SPACE (START       (LOADS AND EXECUTES PROGRAM)       SIM00970
C                                                                        SIM00980
C     SUBSEQUENT PROGRAM RUNS CAN ELIMINATE "FORTVS SPACE" IF NO         SIM00990
C     CHANGES HAVE BEEN MADE TO THE PROGRAM, AND CAN ELIMINATE           SIM01000
C     RUNNING THE EXEC FILE.                                             SIM01010
C                                                                        SIM01020
C     FI 4 DISK THESIS INPUT B (PERM                                     SIM01030
C     FI 8 DISK UTILITY DATA  (RECFM VS BLOCK 133 PERM                   SIM01040
C     FI 11 DISK CNTRL OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM           SIM01050
C     FI 13 DISK GAMMA OUTPUT  (RECFM VS BLOCK 133 PERM                  SIM01060
C     FI 14 DISK MODE OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM            SIM01070
```

```
C     FI 16 DISK COST OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM          SIM01080
C     FI 17 DISK PRT  OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM          SIM01090
C     FI 18 DISK ERROR DATA   (RECFM F BLOCK 80 LRECL 80 PERM          SIM01100
C     FI 19 DISK END FILE   (RECFM F BLOCK 80 LRECL 80 PERM            SIM01110
C     FI 20 DISK GMAT FILE (RECFM F BLOCK 80 LRECL 80 PERM             SIM01120
C                                                                      SIM01130
C     ***************************************************************  SIM01140
C                                                                      SIM01150
      PARAMETER (JR=5243, KR=5397, MR=262139)                          SIM01160
C                                                                      SIM01170
C                                                                      SIM01180
      MIN =1.00                                                        SIM01190
C                                                                      SIM01200
      WT=1.0D00                                                        SIM01210
      PI = 4.0D0 * ATAN(1.0D0)                                         SIM01220
C                                                                      SIM01230
C     ***************************************************************  SIM01240
C     ******          READ LAMA AND UGVEX MATRICIES          ******    SIM01250
C     ***************************************************************  SIM01260
C                                                                      SIM01270
      CALL EXCMS ('CLRSCRN')                                           SIM01280
      WRITE(6,1008)                                                    SIM01290
      WRITE(6,*) '                    READING LAMA AND UGVEX MATRICIES' SIM01300
      WRITE(6,*) ' '                                                   SIM01310
C     THIS SECTION READS THE LAMA VECTOR AND THE UGVEX                 SIM01320
C     MATRIX AND STORES THEM IN MEMORY FOR FURTHER RECALL OF           SIM01330
C     DESIRED LOCATION DATA.                                           SIM01340
C                                                                      SIM01350
      READ(4,1001) NAM                                                 SIM01360
      READ(4,1002)(LAMA(I),I=1,100)                                    SIM01370
      READ(4,1001) NAM                                                 SIM01380
      DO 5 J = 1,100                                                   SIM01390
         READ(4,1002)(UGVEX(I,J),I=1,684)                              SIM01400
5     CONTINUE                                                         SIM01410
C                                                                      SIM01420
1001  FORMAT(1X,A6)                                                    SIM01430
1002  FORMAT(1X,8E15.8)                                                SIM01440
1008  FORMAT (1X,////)                                                 SIM01450
C                                                                      SIM01460
500   CALL EXCMS ('CLRSCRN')                                           SIM01470
C                                                                      SIM01480
C     ***************       STARTING MODE NUMBER      ***************  SIM01490
C     ** SMODE 7 TO 100 (INTEGER) ****                                 SIM01500
      SMODE= 7                                                         SIM01510
C                                                                      SIM01520
      WRITE (16,700) SMODE                                             SIM01530
700   FORMAT (' ','STARTING MODE NUMBER:  ',I2)                        SIM01540
C                                                                      SIM01550
C     ******************    NUMBER OF MODES TO SCAN    ***************  SIM01560
C     ** MODE 1 TO 93 (INTEGER)                                        SIM01570
C                                                                      SIM01580
      MODE=20                                                          SIM01590
C                                                                      SIM01600
      EMODE = SMODE + MODE - 1                                         SIM01610
C                                                                      SIM01620
```

```
      WRITE (16,701) MODE                                                SIM01630
701   FORMAT (' ','NUMBER OF MODES SCANNED:   ',I2)                      SIM01640
C                                                                        SIM01650
C     **************    NOISE INPUT POSITION      ********************   SIM01660
C     ** NODE 1 TO 114 (INTEGER) (IF 0 THEN NO NOISE INPUT)             SIM01670
      NODE= 8                                                            SIM01680
C                                                                        SIM01690
      WRITE (16,702) NODE                                                SIM01700
702   FORMAT (' ',' NOISE NODE LOCATION:    ',I5)                        SIM01710
C                                                                        SIM01720
C     ************ START AND STOP FOR PLANT                             SIM01730
      SN=7                                                               SIM01740
      FN=20                                                              SIM01750
      NS=SN*2-1                                                          SIM01760
      NF=SN*2+2*FN-2                                                     SIM01770
      WRITE (16,899) SN,FN                                               SIM01780
899   FORMAT (' ','PLANT -- SN= ',I5,'  FN= ',I5)                        SIM01790
C     ***************          SAMPLING TIME          ****************   SIM01800
C     ** SAMPT MUST BE LESS THAN OR EQUAL TO SAMPTM **                   SIM01810
      SAMPT = 0.05                                                       SIM01820
         SAMPTM = ((2.0D0*PI)/SQRT(LAMA(EMODE)))/1.0D01                  SIM01830
         IF (SAMPT.GE.SAMPTM) THEN                                       SIM01840
              SAMPT=SAMPTM                                               SIM01850
         ENDIF                                                           SIM01860
C                                                                        SIM01870
      WRITE (16,900) MIN                                                 SIM01880
900   FORMAT (' ',2X,'MIN:   ',F8.3)                                     SIM01890
C                                                                        SIM01900
      WRITE (16,703) SAMPT, SAMPTM                                       SIM01910
703   FORMAT (' ','SAMPLING TIME:   ',D12.4,2X,'SAMPTM= ',D15.8)         SIM01920
C                                                                        SIM01930
C     ******************        DAMPING FACTOR        ****************   SIM01940
C     ** DAMP 0.0 TO 1.0 (REAL*8)                                       SIM01950
      DAMP=.01                                                           SIM01960
C                                                                        SIM01970
      WRITE (16,704) DAMP                                                SIM01980
704   FORMAT (' ','DAMPING FACTOR:   ',D12.4)                            SIM01990
C                                                                        SIM02000
C                                                                        SIM02010
C     **** PLANT NOISE VARIANCE ****                                     SIM02020
C     ** PNVARX, PNVARY, PNVARZ GT 0.0                                  SIM02030
      SF1=2.5D06                                                         SIM02040
      SF=1.0D00                                                          SIM02050
C                                                                        SIM02060
      PNVARX=1.0D00*SF1                                                  SIM02070
      PNVARY=1.0D00*SF1                                                  SIM02080
      PNVARZ=1.0D00*SF1                                                  SIM02090
C                                                                        SIM02100
C                                                                        SIM02110
C                                                                        SIM02120
C     **** MEASUREMENT NOISE VARIANCE ***                                SIM02130
C     ** MNVARX, MNVARY, MNVARZ GT 0.0                                  SIM02140
      MNVARX=1.0D-03 *SF                                                 SIM02150
      MNVARY=1.0D-03 *SF                                                 SIM02160
```

```
      MNVARZ=1.0D-03 *SF                                                SIM02170
C                                                                       SIM02180
C                                                                       SIM02190
      WRITE (16,711)                                                    SIM02200
711   FORMAT(' ','PLANT NOISE VARIANCE:  ')                             SIM02210
      WRITE (16,712)                                                    SIM02220
712   FORMAT(' ',6X,'PNVARX',13X,'PNVARY',13X,'PNVARZ')                 SIM02230
      WRITE (16,713) PNVARX, PNVARY, PNVARZ                             SIM02240
713   FORMAT(' ',2X,E15.8,2X,E15.8,2X,E15.8)                            SIM02250
      WRITE(16,714)                                                     SIM02260
714   FORMAT(' ','MEASUREMENT NOISE:')                                  SIM02270
      WRITE(16,715)                                                     SIM02280
715   FORMAT(' ',6X,'MNVARX',13X,'MNVARY',13X,'MNVARZ')                 SIM02290
      WRITE(16,713) MNVARX,MNVARY,MNVARZ                                SIM02300
C                                                                       SIM02310
510   CALL EXCMS ('CLRSCRN')                                            SIM02320
      WRITE (6,1008)                                                    SIM02330
      WRITE (6,*) '                                PROGRAM RUNNING'     SIM02340
C                                                                       SIM02350
C     ************       NOISE INPUT LOCATION        **************     SIM02360
C                                                                       SIM02370
      ROWN3 = NODE*6                                                    SIM02380
      ROWN2 = (NODE*6) - 1                                              SIM02390
      ROWN1 = (NODE*6) - 2                                              SIM02400
      COUNT = 0                                                         SIM02410
C                                                                       SIM02420
C                                                                       SIM02430
C     ************       INITIALIZE MATRICIES       ******************  SIM02440
C                                                                       SIM02450
      DO 48 K=1,50                                                      SIM02460
         IDENT(K,K)=1.0                                                 SIM02470
48    CONTINUE                                                          SIM02480
C                                                                       SIM02490
      DO 54 K = 1, 200                                                  SIM02500
          X(K) = 0.0                                                    SIM02510
54    CONTINUE                                                          SIM02520
C                                                                       SIM02530
C                                                                       SIM02540
      WRITE(6,1008)                                                     SIM02550
      WRITE (6,*) ' INITIALIZE RMN AND QPN MATRICES   '                 SIM02560
C     *** INITIALIZE RMN AND QPN MATRICES ***                           SIM02570
C                                                                       SIM02580
      DO 60 I=1,3                                                       SIM02590
         DO 58 J=1,3                                                    SIM02600
         RMN(I,J)=0.0                                                   SIM02610
         QPN(I,J)=0.0                                                   SIM02620
58       CONTINUE                                                       SIM02630
60    CONTINUE                                                          SIM02640
C                                                                       SIM02650
      RMN(1,1)=MNVARX**2                                                SIM02660
      RMN(2,2)=MNVARY**2                                                SIM02670
      RMN(3,3)=MNVARZ**2                                                SIM02680
      QPN(1,1)=PNVARX**2                                                SIM02690
      QPN(2,2)=PNVARY**2                                                SIM02700
```

```
      QPN(3,3)=PNVARZ**2.0                                                SIM02710
C                                                                         SIM02720
C                                                                         SIM02730
      WRITE(6,1008)                                                       SIM02740
      WRITE(6,*)  ' ENTER STMTRX    '                                     SIM02750
C                                                                         SIM02760
C     ***************************************************************     SIM02770
C     ******            BEGIN MAIN PROGRAM                       ******   SIM02780
C     ***************************************************************     SIM02790
C                                                                         SIM02800
      CALL STMTRX(EMODE,SMODE,SAMPT,DAMP,PHI,GAMMA,A,B,LAMA,UGVEX,C,      SIM02810
     +   ROWN1,ROWN2,ROWN3,BN)                                            SIM02820
C                                                                         SIM02830
C                                                                         SIM02840
      WRITE (16,1008)                                                     SIM02850
      DO 11000 I=1,200                                                    SIM02860
         DO 10900 J=1,3                                                   SIM02870
         C(J,I)= C( J,I)*SF                                               SIM02880
10900    CONTINUE                                                         SIM02890
11000 CONTINUE                                                            SIM02900
C                                                                         SIM02910
C     *** PRE-LOOP PORTION OF KALMAN FILTER                               SIM02920
C                                                                         SIM02930
      M2=2*MODE                                                           SIM02940
      JP=2*SMODE-1                                                        SIM02950
      JQ=2*EMODE                                                          SIM02960
      DO 90 I=1,50                                                        SIM02970
         XH(I)=0.0                                                        SIM02980
90    CONTINUE                                                            SIM02990
C                                                                         SIM03000
      DO 9971 I=1,M2                                                      SIM03010
         READ (20,*) G(I,1), G(I,2), G(I,3)                               SIM03020
9971  CONTINUE                                                            SIM03030
C                                                                         SIM03040
C                                                                         SIM03050
      WRITE (14,1008)                                                     SIM03060
      DO 384 I=1,M2                                                       SIM03070
      WRITE (14,5350)   G(I,1),G(I,2),G(I,3)                              SIM03080
384   CONTINUE                                                            SIM03090
5350  FORMAT (' ',2X,D15.8,2X,D15.8,2X,D15.8)                             SIM03100
C                                                                         SIM03110
C                                                                         SIM03120
C     ***************************************************************     SIM03130
C     ******     THIS SECTION COMPUTES THE STATE UPDATE      ******      SIM03140
C     ***************************************************************     SIM03150
      DO 9771 I=1,100                                                     SIM03160
      E2(I)=0.0                                                           SIM03170
      E3(I)=0.0                                                           SIM03180
      XS(I)=0.0                                                           SIM03190
9771  CONTINUE                                                            SIM03200
      ESS =0.0                                                            SIM03210
      COUNT = 0                                                           SIM03220
      ENERGY = 0.0D0                                                      SIM03230
      TIME = 0.0                                                          SIM03240
      CGN=0.0                                                             SIM03250
```

```
      CTG=0.0                                                          SIM03260
C     ******  SETS LOOP FOR THE ITERATIONS NECESSARY TO OBSERVE  ******  SIM03270
C     ******  THE SYSTEM FOR THE NUMBER OF MINUTES SPECIFIED     ******  SIM03280
      WRITE (6,1008)                                                   SIM03290
      WRITE (6,*) '            START STATE UPDATE     '                SIM03300
      LOOP = INT((MIN*60.0)/SAMPT)                                     SIM03310
      PRT= (DBLE(LOOP))/30.0                                           SIM03320
      CTT=0.0                                                          SIM03330
C                                                                      SIM03340
      DO 400 L  = 0, LOOP                                              SIM03350
         TIME = DBLE(L)*SAMPT                                          SIM03360
C                                                                      SIM03370
         IF(L.EQ.0)THEN                                                SIM03380
            IMPLSE =(1.0D06*SF1)/(DSQRT(SAMPT))                        SIM03390
         ELSE                                                          SIM03400
            IMPLSE = 0.0D0                                             SIM03410
         ENDIF                                                         SIM03420
C                                                                      SIM03430
      TO=0.0                                                           SIM03440
C     ****** RANDOM NUMBER GENERATOR ******                            SIM03450
C                                                                      SIM03460
      DO 101 I=1,6                                                     SIM03470
      ISEED=MOD(ISEED*JR+KR,MR)                                        SIM03480
      RND1=(DBLE(ISEED)+0.5D00)/DBLE(MR)                               SIM03490
      ISEED=MOD(ISEED*JR+KR,MR)                                        SIM03500
      RND2=(DBLE(ISEED)+0.5D00)/DBLE(MR)                               SIM03510
      RNDM(I)=DSQRT(-2.0*DLOG(RND1))*DCOS(6.2831853D00*RND2)           SIM03520
101   CONTINUE                                                         SIM03530
C     **********************                                           SIM03540
      CTT=CTT+1.0                                                      SIM03550
C     ***** START OF STATE UPDATE ***                                  SIM03560
C                                                                      SIM03570
C     *** COMPUTE AX°200  = A°200 X 200  * X°200                       SIM03580
C                                                                      SIM03590
C                                                                      SIM03600
C     *** COMPUTE AX  = A*X                                            SIM03610
C                                                                      SIM03620
      JK=SMODE*2-2                                                     SIM03630
      JP=JK+1                                                          SIM03640
      JQ=2*EMODE                                                       SIM03650
C                                                                      SIM03660
C                                                                      SIM03670
      DO 5015 I=NS,NF                                                  SIM03680
         SUM=0.0                                                       SIM03690
              DO 5010 K=NS,NF                                          SIM03700
              SUM=SUM+A(I,K)*X(K)                                      SIM03710
5010          CONTINUE                                                 SIM03720
         AX(I)=SUM                                                     SIM03730
5015  CONTINUE                                                         SIM03740
C                                                                      SIM03750
C     *** COMPUTE WD°3                                                 SIM03760
C                                                                      SIM03770
      WD(1)=PNVARX*RNDM(1)*TO+IMPLSE                                   SIM03780
      WD(2)=PNVARY*RNDM(2)*TO                                          SIM03790
      WD(3)=PNVARZ*RNDM(3)*TO                                          SIM03800
C                                                                      SIM03810
```

```
C                                                                       SIM03820
C     *** COMPUTE BNWD°200 =BN°200 X 3  * WD°3                          SIM03830
C                                                                       SIM03840
      DO 5035 I=NS,NF                                                   SIM03850
         SUM=0.0                                                        SIM03860
              DO 5030 K=1,3                                             SIM03870
              SUM=SUM+BN(I,K)*WD(K)                                     SIM03880
5030          CONTINUE                                                  SIM03890
         BNWD(I)=SUM                                                    SIM03900
5035  CONTINUE                                                          SIM03910
C                                                                       SIM03920
C     *** COMPUTE X°200 =AX°200  + BNWD°200                             SIM03930
C                                                                       SIM03940
      DO 5040 I=NS,NF                                                   SIM03950
         X(I)= AX(I) + BNWD(I)                                          SIM03960
         IF (DABS(X(I)).LT. 1.0D-60) THEN                               SIM03970
              X(I)=1.0D-60                                              SIM03980
         END IF                                                         SIM03990
C                                                                       SIM04000
C                                                                       SIM04010
C                                                                       SIM04020
5040  CONTINUE                                                          SIM04030
C                                                                       SIM04040
C     *** COMPUTE V°3                                                   SIM04050
C                                                                       SIM04060
      V(1)=MNVARX*RNDM(4)                                               SIM04070
      V(2)=MNVARY*RNDM(5)                                               SIM04080
      V(3)=MNVARZ*RNDM(6)                                               SIM04090
C                                                                       SIM04100
C     *** COMPUTE Y°3  = C°3 X 200  * X°200  + V°3                      SIM04110
C                                                                       SIM04120
      DO 5050 I=1,3                                                     SIM04130
         SUM=0.0                                                        SIM04140
              DO 5045 K=NS,NF                                           SIM04150
              SUM=SUM+C(I,K)*X(K)                                       SIM04160
5045          CONTINUE                                                  SIM04170
         Y(I)=SUM+V(I)                                                  SIM04180
5050  CONTINUE                                                          SIM04190
C                                                                       SIM04200
C     **********************                                            SIM04210
C                                                                       SIM04220
C     *** START OF KALMAN FILTER ***                                    SIM04230
C                                                                       SIM04240
      M2=2*MODE                                                         SIM04250
C                                                                       SIM04260
C                                                                       SIM04270
C     *** COMPUTE XH1 = A*XH                                            SIM04280
C                                                                       SIM04290
      DO 300 I=JP,JQ                                                    SIM04300
      SUM=0.0                                                           SIM04310
         DO 295 K=JP,JQ                                                 SIM04320
         SUM=SUM+A(I,K) * XH(K)                                         SIM04330
295      CONTINUE                                                       SIM04340
      XH1(I)=SUM                                                        SIM04350
300   CONTINUE                                                          SIM04360
C     ****************                                                  SIM04370
```

```
C                                                                       SIM04380
C     *** COMPUTE DY = Y - C*XH1                                        SIM04390
C                                                                       SIM04400
      DO 315 I=1,3                                                      SIM04410
      SUM=0.0                                                           SIM04420
         DO 310 K=JP,JQ                                                 SIM04430
         SUM=SUM+C(I,K)*XH1(K)                                          SIM04440
310      CONTINUE                                                       SIM04450
      DY(I)=Y(I)-SUM                                                    SIM04460
315   CONTINUE                                                          SIM04470
C                                                                       SIM04480
C     ********************                                              SIM04490
C                                                                       SIM04500
C     *** COMPUTE XH = XH1 + G*DY                                       SIM04510
C                                                                       SIM04520
      DO 325 I=1,M2                                                     SIM04530
         J1=JP-1+I                                                      SIM04540
         SUM=0.0                                                        SIM04550
              DO 320 K=1,3                                              SIM04560
              SUM=SUM+G(I,K)*DY(K)                                      SIM04570
320           CONTINUE                                                  SIM04580
         XH(J1)=XH1(J1)+SUM                                             SIM04590
         IF (DABS(XH(J1)).LT.1.0D-60) THEN                              SIM04600
              XH(J1)=1.0*D-60                                           SIM04610
         END IF                                                         SIM04620
C                                                                       SIM04630
325   CONTINUE                                                          SIM04640
C                                                                       SIM04650
C                                                                       SIM04660
C                                                                       SIM04670
C     ****** END OF KALMAN ROUTINES *******                             SIM04680
C                                                                       SIM04690
C     *** COMPUTATION OF ESUM ***                                       SIM04700
      DO 340 I=JP,JQ                                                    SIM04710
      XDEL= X(I)-XH(I)                                                  SIM04720
      XDEL1=XDEL*XDEL*SAMPT                                             SIM04730
      E2(I)=E2(I)+XDEL1                                                 SIM04740
      XS(I)=XS(I)+X(I)*X(I)*SAMPT                                       SIM04750
      E3(I)=E2(I)/XS(I)                                                 SIM04760
340   CONTINUE                                                          SIM04770
C                                                                       SIM04780
      CGN=CGN+1.0                                                       SIM04790
      IF (CTT.EQ.1.0.OR.CGN.GT.PRT) THEN                                SIM04800
C                                                                       SIM04810
      WRITE (6,*) 'TIME= ', TIME, ' SEC.'                               SIM04820
C                                                                       SIM04830
      WRITE (17,1008)                                                   SIM04840
      WRITE (16,1008)                                                   SIM04850
      WRITE (16,2100) TIME                                              SIM04860
C                                                                       SIM04870
      WRITE (17,2100) TIME                                              SIM04880
2100  FORMAT(' ','TIME=  ',F9.3)                                        SIM04890
      DO 380 I=JP , JQ                                                  SIM04900
      WRITE (16,4500) I,X(I) ,I ,XH(I)                                  SIM04910
C                                                                       SIM04920
```

```
      WRITE (17,4530) I,E2(I)  ,E3(I)   , XS(I)                          SIM04930
380   CONTINUE                                                            SIM04940
C                                                                         SIM04950
C                                                                         SIM04960
C                                                                         SIM04970
C                                                                         SIM04980
      CGN=0.0                                                             SIM04990
      END IF                                                              SIM05000
4500  FORMAT (' ',' X(',I3,')= ',D15.8,2X,'XH(',I3,')= ',D15.8)           SIM05010
4530  FORMAT (' ',5X,I5,5X,3 D15.8)                                       SIM05020
C                                                                         SIM05030
400   CONTINUE                                                            SIM05040
C                                                                         SIM05050
C                                                                         SIM05060
      DO 401 I=JP,JQ                                                      SIM05070
         WRITE (19,4530) I, E2(I) ,E3(I), XS(I)                           SIM05080
401   CONTINUE                                                            SIM05090
C                                                                         SIM05100
C                                                                         SIM05110
C                                                                         SIM05120
C                                                                         SIM05130
599   STOP                                                                SIM05140
      END                                                                 SIM05150
C                                                                         SIM05160
C                                                                         SIM05170
C     ******************************************************************* SIM05180
C     THIS SUBROUTINE COMPUTES THE STATE TRANSITION MATRIX FOR EACH       SIM05190
C     OF THE 100 MODES                                                    SIM05200
C     ******************************************************************* SIM05210
C                                                                         SIM05220
      SUBROUTINE STMTRX(EMODE,SMODE,T,D,PHI,GAMMA,A,B,LAMA,UGVEX,C,       SIM05230
     +         ROWN1,ROWN2,ROWN3,BN)                                      SIM05240
C                                                                         SIM05250
      REAL*8 WN,GMA,PHI(2,2,100),GAMMA(2,100),EGT,T,COSW1T,SINW1T         SIM05260
      REAL*8 W1,D,A(200,200),B(200,3),C(3,200),BN(200,3)                  SIM05270
      REAL LAMA(100),UGVEX(684,100)                                       SIM05280
      INTEGER SMODE,R,EMODE,JJ,KK,ROWN1,ROWN2,ROWN3                       SIM05290
C                                                                         SIM05300
C                                                                         SIM05310
      DO 600 I = 1    ,100                                                SIM05320
         WN = DBLE(SQRT(LAMA(I)))                                         SIM05330
         GMA = D*WN/2.0                                                   SIM05340
         EGT = DEXP(-GMA*T)                                               SIM05350
         W1 = DSQRT((WN**2)-(GMA**2))                                     SIM05360
         COSW1T = DCOS(W1*T)                                              SIM05370
         SINW1T = DSIN(W1*T)                                              SIM05380
C                                                                         SIM05390
C                                                                         SIM05400
C                                                                         SIM05410
C                                                                         SIM05420
         IF(WN.EQ.0)THEN                                                  SIM05430
              PHI(1,1,I) = EGT*COSW1T                                     SIM05440
              PHI(1,2,I) = T                                              SIM05450
              PHI(2,1,I) = 0                                              SIM05460
              PHI(2,2,I) = EGT*COSW1T                                     SIM05470
C                                                                         SIM05480
```

```
C                                                                       SIM05490
C                                                                       SIM05500
C                                                                       SIM05510
C                                                                       SIM05520
C                                                                       SIM05530
            GAMMA(1,I) = 0                                              SIM05540
            GAMMA(2,I) = 0                                              SIM05550
         ELSE                                                           SIM05560
C                                                                       SIM05570
C                                                                       SIM05580
C                                                                       SIM05590
C                                                                       SIM05600
         PHI(1,1,I) = EGT*(COSW1T + (GMA*(W1**(-1)))*SINW1T)            SIM05610
         PHI(1,2,I) = (W1**(-1))*EGT*SINW1T                             SIM05620
         PHI(2,1,I) = -(WN**2)*(W1**(-1))*EGT*SINW1T                    SIM05630
         PHI(2,2,I) = EGT*(COSW1T - (GMA*(W1**(-1)))*SINW1T)            SIM05640
C                                                                       SIM05650
C                                                                       SIM05660
C                                                                       SIM05670
C                                                                       SIM05680
      GAMMA(1,I)=(WN**(-2))*(1.0D0-EGT*COSW1T -EGT*(GMA/W1)*SINW1T)     SIM05690
         GAMMA(2,I) = (W1**(-1))*EGT*SINW1T                             SIM05700
C                                                                       SIM05710
C                                                                       SIM05720
C                                                                       SIM05730
C                                                                       SIM05740
         ENDIF                                                          SIM05750
C                                                                       SIM05760
C                                                                       SIM05770
C                                                                       SIM05780
600   CONTINUE                                                          SIM05790
C                                                                       SIM05800
C                                                                       SIM05810
      R = 1                                                             SIM05820
C                                                                       SIM05830
      DO 610 K = 1    ,100                                              SIM05840
C                                                                       SIM05850
C                                                                       SIM05860
C                                                                       SIM05870
C                                                                       SIM05880
C                                                                       SIM05890
         A(R,R) = PHI(1,1,K)                                            SIM05900
         A(R,R+1) = PHI(1,2,K)                                          SIM05910
         A(R+1,R) = PHI(2,1,K)                                          SIM05920
         A(R+1,R+1) = PHI(2,2,K)                                        SIM05930
C                                                                       SIM05940
C                                                                       SIM05950
C                                                                       SIM05960
C                                                                       SIM05970
C                                                                       SIM05980
C     *** B MATRIX FOR MULTIPLYING CONTROL TORQUES                      SIM05990
C                                                                       SIM06000
         B(R,1) = GAMMA(1,K)*DBLE(UGVEX(412,K))                         SIM06010
         B(R,2) = GAMMA(1,K)*DBLE(UGVEX(413,K))                         SIM06020
         B(R,3) = GAMMA(1,K)*DBLE(UGVEX(414,K))                         SIM06030
         B(R+1,1) = GAMMA(2,K)*DBLE(UGVEX(412,K))                       SIM06040
```

```
         B(R+1,2) = GAMMA(2,K)*DBLE(UGVEX(413,K))                    SIM06050
         B(R+1,3) = GAMMA(2,K)*DBLE(UGVEX(414,K))                    SIM06060
C                                                                    SIM06070
C                                                                    SIM06080
C                                                                    SIM06090
C                                                                    SIM06100
C                                                                    SIM06110
C                                                                    SIM06120
C                                                                    SIM06130
C     *** BN MATRIX FOR MULTIPLYING THE NOISE DISTURBANCES           SIM06140
C                                                                    SIM06150
C                                                                    SIM06160
C                                                                    SIM06170
C                                                                    SIM06180
      BN(R,1)=GAMMA(1,K)*DBLE(UGVEX(ROWN1,K))                        SIM06190
      BN(R,2)=GAMMA(1,K)*DBLE(UGVEX(ROWN2,K))                        SIM06200
      BN(R,3)=GAMMA(1,K)*DBLE(UGVEX(ROWN3,K))                        SIM06210
      BN(R+1,1)=GAMMA(2,K)*DBLE(UGVEX(ROWN1,K))                      SIM06220
      BN(R+1,2)=GAMMA(2,K)*DBLE(UGVEX(ROWN2,K))                      SIM06230
      BN(R+1,3)=GAMMA(2,K)*DBLE(UGVEX(ROWN3,K))                      SIM06240
C                                                                    SIM06250
C                                                                    SIM06260
C                                                                    SIM06270
C                                                                    SIM06280
C                                                                    SIM06290
C                                                                    SIM06300
         R = R+2                                                     SIM06310
610   CONTINUE                                                       SIM06320
C                                                                    SIM06330
C     *** C MATRIX PRODUCTION ***                                    SIM06340
C                                                                    SIM06350
C                                                                    SIM06360
C                                                                    SIM06370
C                                                                    SIM06380
      JJ=-1                                                          SIM06390
      DO 640 I=1,100                                                 SIM06400
      JJ=JJ+1                                                        SIM06410
      KK=I         +JJ                                               SIM06420
C                                                                    SIM06430
C                                                                    SIM06440
C                                                                    SIM06450
      C(1,KK) = DBLE(UGVEX(418,I))                                   SIM06460
      C(2,KK) = DBLE(UGVEX(419,I))                                   SIM06470
      C(3,KK) = DBLE(UGVEX(420,I))                                   SIM06480
C                                                                    SIM06490
C                                                                    SIM06500
C                                                                    SIM06510
      KK=KK+1                                                        SIM06520
C                                                                    SIM06530
      C(1,KK)=0.0                                                    SIM06540
      C(2,KK)=0.0                                                    SIM06550
      C(3,KK)=0.0                                                    SIM06560
C                                                                    SIM06570
640   CONTINUE                                                       SIM06580
C                                                                    SIM06590
C                                                                    SIM06600
```

```
C
C                                                                SIM06610
                                                                 SIM06620
      RETURN                                                     SIM06630
      END                                                        SIM06640
```

APPENDIX C. PROGRAM TO ESTIMATE NOISE IN KALMAN FILTER FROM UNOBSERVED MODES

```
C                                                                               SPA00010
C     ********************************************************************      SPA00020
C     ******                    SPAC 24                               ******      SPA00030
C     ******  ADAPTED TO RUN N MODES OF THE PLANT AND                 ******      SPA00040
C     ******  COMPUTE THE NOISE IN THE KALMAN FILTER                  ******      SPA00050
C     ******  FROM THE UNOBSERVED MODES                               ******      SPA00060
C     ********************************************************************      SPA00070
C                                                                               SPA00080
C                                                                               SPA00090
C     ********************************************************************      SPA00100
C     ******              VARIABLE DECLARATIONS                       ******      SPA00110
C     ********************************************************************      SPA00120
C                                                                               SPA00130
      EXTERNAL STMTRX,EXCMS                                                     SPA00140
      CHARACTER*6 NAM                                                           SPA00150
      CHARACTER*1 AGAIN,CORECT,RAGAIN                                           SPA00160
      INTEGER ROWN1,ROWN2,ROWN3,COUNT,NODE,MODE,KQ,EMODE,SMODE,R2M,C2M          SPA00170
      INTEGER CT,CF,KADJ,CFADJ,LOOP,PRNT,JJ,JK,N1,JR,KR,MR,ISEED,M2            SPA00180
      INTEGER NO,                    NS, NF, SN, FN                           SPA00190
      INTEGER JL,J1,JM , JP, JQ, KA, KB, KC, KD, KE, KF, KG                    SPA00200
C                                                                               SPA00210
C                                                                               SPA00220
C                                                                               SPA00230
      REAL LAMA(100), UGVEX(684,100),RNODE,RMODE,MIN                            SPA00240
      REAL*8 PHI(2,2,100),GAMMA(2,100),EGT,GMA,WN,W1,X1T,X2T,TIME               SPA00250
      REAL*8 A(200,200),B(200,3),F(3, 50),IMPLSE,ENERGY                         SPA00260
      REAL*8 COSW1T,SINW1T,X(200)                                               SPA00270
      REAL*8 DAMP,SAMPT,PI,SAMPTM,SUM1,SUM2,SUM3,SUMC                           SPA00280
      REAL*8 C(9,200), RMN(3,3), QPN(3,3)                                       SPA00290
      REAL*8 BN(200,3)                                                          SPA00300
      REAL*8 PNVARX, PNVARY, PNVARZ                                             SPA00310
      REAL*8 MNVARX, MNVARY, MNVARZ                                             SPA00320
      REAL*8 SUM, RNDM(6), RND1, RND2                                           SPA00330
      REAL*8 ES,ED,ESUM,CGN,PRT                                                 SPA00340
      REAL*8 WT , WD(3),  BNWD(200), EX1(9)                                     SPA00350
      REAL*8 EX(9),AX(200) , SF , TO, CTT, ESS                                  SPA00360
      REAL*8 CTG, XDEL,  XDEL1, ERS, PRT1                                       SPA00370
      REAL*8 SF1                                                                SPA00380
C                                                                               SPA00390
C     ********************************************************************      SPA00400
C     ******              VARIABLE DEFINITIONS                        ******      SPA00410
C     ********************************************************************      SPA00420
C                                                                               SPA00430
C     STMTRX = SUBROUTINE EXTABLISHES STATE TRANSITION MATRICIES                SPA00440
C     LAMA = VECTOR OF THE SQUARE OF THE NATURAL FREQUENCIES                    SPA00450
C     UGVEX = MODE POSITONS AND SLOPES OF THE NODAL POINTS                      SPA00460
C     PHI = STATE TRANSITION MATRICIES FOR EACH MODE                            SPA00470
C     GAMMA = INPUT TRANSITION MATRIX                                           SPA00480
C     A = DIAGONAL MATRIX CONSISTING OF PHI                                     SPA00490
```

```
C     B = INPUT MATRIX OF GAMMA AND CONTROL SLOPES                          SPA00500
C     DAMP = DAMPING FACTOR                                                 SPA00510
C     SAMPT = SAMPLING TIME                                                 SPA00520
C     IMPLSE = IMPULSE INPUT FUNCTION                                       SPA00530
C     MIN = NUMBER OF MINUTES SYSTEM WILL BE OBSERVED                       SPA00540
C     SMODE = NUMBER OF STARTING MODE (INT)                                 SPA00550
C     MODE = NUMBER OF MODES (INT)                                          SPA00560
C     EMODE = NUMBER OF THE LAST MODE (INT)                                 SPA00570
C     NODE = NUMBER OF THE NOISE INPUT MODE (INT)                           SPA00580
C      *** NOISE SLOPE LOCATIONS IN DATA MATRIX ***                         SPA00590
C     ROWN1 = X-SLOPE LOCATION                                              SPA00600
C     ROWN2 = Y-SLOPE LOCATION                                              SPA00610
C     ROWN3 = Z-SLOPE LOCATION                                              SPA00620
C     C = OUTPUT MATRIX FOR Y                                               SPA00630
C     IDENT = IDENTITY MATRIX                                               SPA00640
C     RMN = MEASUREMENT NOISE COVARIANCE MATRIX                             SPA00650
C     QPN = PLANT NOISE COVARIANCE MATRIX                                   SPA00660
C     PNVARX = PLANT NOISE X-SLOPE VARIANCE                                 SPA00670
C     PNVARY = PLANT NOISE Y-SLOPE VARIANCE                                 SPA00680
C     PNVARZ = PLANT NOISE Z-SLOPE VARIANCE                                 SPA00690
C     MNVARX = MEASUREMENT NOISE X-SLOPE VARIANCE                           SPA00700
C     MNVARY = MEASUREMENT NOISE Y-SLOPE VARIANCE                           SPA00710
C     MNVARZ = MEASUREMENT NOISE Z-SLOPE VARIANCE                           SPA00720
C     ISEED = INITIALIZATION FOR RANDOM NUMBER GENERATOR                    SPA00730
C     RNDM = RANDOM NUMBERS USED FOR WHITE NOISE IN MEASUREMENTS AND        SPA00740
C             IN PLANT FORCES                                               SPA00750
C     BN = B MATRIX TO MULTIPLY NOISE DISTURBANCES                          SPA00760
C                                                                           SPA00770
C                                                                           SPA00780
C                                                                           SPA00790
C     ************      SAMPLE OF SPACE EXEC FILE      ********************* SPA00800
C                                                                           SPA00810
C     THIS FILE MUST BEGIN IN COLUMN 1 AND RUN WITH THE FOLLOWING           SPA00820
C     SEQUENCE FOR THE INITIAL RUN OF THE PROGRAM:                          SPA00830
C                                                                           SPA00840
C             FORTVS SPACE            (COMPILES PROGRAM)                    SPA00850
C             SPACE                   (EXECUTES EXEC FILE)                  SPA00860
C             LOAD SPACE (START       (LOADS AND EXECUTES PROGRAM)          SPA00870
C                                                                           SPA00880
C     SUBSEQUENT PROGRAM RUNS CAN ELIMINATE "FORTVS SPACE" IF NO            SPA00890
C     CHANGES HAVE BEEN MADE TO THE PROGRAM, AND CAN ELIMINATE              SPA00900
C     RUNNING THE EXEC FILE.                                                SPA00910
C                                                                           SPA00920
C     FI 4 DISK THESIS INPUT (PERM                                          SPA00930
C     FI 8 DISK UTILITY DATA  (RECFM VS BLOCK 133 PERM                      SPA00940
C     FI 11 DISK CNTRL OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM              SPA00950
C     FI 13 DISK GAMMA OUTPUT  (RECFM VS BLOCK 133 PERM                     SPA00960
C     FI 14 DISK MODE OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM               SPA00970
C     FI 16 DISK COST OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM               SPA00980
C     FI 17 DISK PRT  OUTPUT  (RECFM F BLOCK 80 LRECL 80 PERM               SPA00990
C     FI 18 DISK ERROR DATA   (RECFM F BLOCK 80 LRECL 80 PERM               SPA01000
C     FI 19 DISK END FILE   (RECFM F BLOCK 80 LRECL 80 PERM                 SPA01010
C     FI 20 DISK GMAT FILE (RECFM F BLOCK 80 LRECL 80 PERM                  SPA01020
C                                                                           SPA01030
C     ************************************************************************ SPA01040
C                                                                           SPA01050
```

```
      PARAMETER (JR=5243, KR=5397, MR=262139)                          SPA01060
C                                                                      SPA01070
C                                                                      SPA01080
      MIN = 15.0                                                       SPA01090
C                                                                      SPA01100
      WT=1.0D00                                                        SPA01110
      PI = 4.0D0 * ATAN(1.0D0)                                         SPA01120
C                                                                      SPA01130
C     ***************************************************************  SPA01140
C     ******          READ LAMA AND UGVEX MATRICIES          ******    SPA01150
C     ***************************************************************  SPA01160
C                                                                      SPA01170
      CALL EXCMS ('CLRSCRN')                                           SPA01180
      WRITE(6,1008)                                                    SPA01190
      WRITE(6,*) '                    READING LAMA AND UGVEX MATRICIES' SPA01200
      WRITE(6,*) ' '                                                   SPA01210
C     THIS SECTION READS THE LAMA VECTOR AND THE UGVEX                 SPA01220
C     MATRIX AND STORES THEM IN MEMORY FOR FURTHER RECALL OF           SPA01230
C     DESIRED LOCATION DATA.                                           SPA01240
C                                                                      SPA01250
      READ(4,1001) NAM                                                 SPA01260
      READ(4,1002)(LAMA(I),I=1,100)                                    SPA01270
      READ(4,1001) NAM                                                 SPA01280
      DO 5 J = 1,100                                                   SPA01290
         READ(4,1002)(UGVEX(I,J),I=1,684)                              SPA01300
5     CONTINUE                                                         SPA01310
C                                                                      SPA01320
1001  FORMAT(1X,A6)                                                    SPA01330
1002  FORMAT(1X,8E15.8)                                                SPA01340
1008  FORMAT(1X,////)                                                  SPA01350
C                                                                      SPA01360
500   CALL EXCMS ('CLRSCRN')                                           SPA01370
C                                                                      SPA01380
C     ***************       STARTING MODE NUMBER      ***************  SPA01390
C     ** SMODE 7 TO 100 (INTEGER) *****                                SPA01400
      SMODE= 17                                                        SPA01410
C                                                                      SPA01420
      WRITE (16,700) SMODE                                             SPA01430
700   FORMAT (' ','STARTING MODE NUMBER:  ',I2)                        SPA01440
C                                                                      SPA01450
C     ******************    NUMBER OF MODES TO SCAN    ***************  SPA01460
C     ** MODE 1 TO 93 (INTEGER)                                        SPA01470
C                                                                      SPA01480
      MODE=3                                                           SPA01490
C                                                                      SPA01500
      EMODE = SMODE + MODE - 1                                         SPA01510
C                                                                      SPA01520
      WRITE (16,701) MODE                                              SPA01530
701   FORMAT (' ','NUMBER OF MODES SCANNED:  ',I2)                     SPA01540
C                                                                      SPA01550
C     ***************    NOISE INPUT POSITION      ******************  SPA01560
C     ** NODE 1 TO 114 (INTEGER) (IF 0 THEN NO NOISE INPUT)            SPA01570
      NODE= 8                                                          SPA01580
C                                                                      SPA01590
      WRITE (16,702) NODE                                              SPA01600
702   FORMAT (' ',' NOISE NODE LOCATION:   ',I5)                       SPA01610
```

```
C                                                                       SPA01620
C     ************* START AND STOP FOR PLANT                           SPA01630
      SN=17                                                             SPA01640
      FN=4                                                              SPA01650
      NS=SN*2-1                                                         SPA01660
      NF=SN*2+2*FN-2                                                    SPA01670
      WRITE (16,899) SN,FN                                              SPA01680
899   FORMAT (' ','PLANT -- SN= ',I5,'  FN= ',I5)                       SPA01690
C     ***************          SAMPLING TIME          ***************   SPA01700
C     ** SAMPT MUST BE LESS THAN OR EQUAL TO SAMPTM **                  SPA01710
      SAMPT = 0.05                                                      SPA01720
         SAMPTM = ((2.0D0*PI)/SQRT(LAMA(EMODE)))/1.0D01                 SPA01730
         IF (SAMPT.GE.SAMPTM) THEN                                      SPA01740
              SAMPT=SAMPTM                                              SPA01750
         ENDIF                                                          SPA01760
C                                                                       SPA01770
      WRITE (16,900) MIN                                                SPA01780
900   FORMAT (' ',2X,'MIN:   ',F8.3)                                    SPA01790
C                                                                       SPA01800
      WRITE (16,703) SAMPT, SAMPTM                                      SPA01810
703   FORMAT (' ','SAMPLING TIME:   ',D12.4,2X,'SAMPTM= ',D15.8)        SPA01820
C                                                                       SPA01830
C     ******************         DAMPING FACTOR         ***************** SPA01840
C     ** DAMP 0.0 TO 1.0 (REAL*8)                                       SPA01850
      DAMP=.01                                                          SPA01860
C                                                                       SPA01870
      WRITE (16,704) DAMP                                               SPA01880
704   FORMAT (' ','DAMPING FACTOR:   ',D12.4)                           SPA01890
C                                                                       SPA01900
      NO=3                                                              SPA01910
C     *** PLANT NOISE VARIANCE ***                                      SPA01920
C     ** PNVARX, PNVARY, PNVARZ GT 0.0                                  SPA01930
C                                                                       SPA01940
      SF=1.0D0                                                          SPA01950
      SF1=2.5D06                                                        SPA01960
      PNVARX=1.0D00*SF1                                                 SPA01970
      PNVARY=1.0D00*SF1                                                 SPA01980
      PNVARZ=1.0D00*SF1                                                 SPA01990
C                                                                       SPA02000
C                                                                       SPA02010
C                                                                       SPA02020
C     *** MEASUREMENT NOISE VARIANCE ***                                SPA02030
C     ** MNVARX, MNVARY, MNVARZ GT 0.0                                  SPA02040
      MNVARX=1.0D-03 *SF                                                SPA02050
      MNVARY=1.0D-03 *SF                                                SPA02060
      MNVARZ=1.0D-03 *SF                                                SPA02070
C                                                                       SPA02080
C                                                                       SPA02090
      WRITE (16,711)                                                    SPA02100
711   FORMAT(' ','PLANT NOISE VARIANCE:   ')                            SPA02110
      WRITE (16,712)                                                    SPA02120
712   FORMAT(' ',6X,'PNVARX',13X,'PNVARY',13X,'PNVARZ')                 SPA02130
      WRITE (16,713) PNVARX, PNVARY, PNVARZ                             SPA02140
713   FORMAT(' ',2X,E15.8,2X,E15.8,2X,E15.8)                            SPA02150
      WRITE(16,714)                                                     SPA02160
714   FORMAT(' ','MEASUREMENT NOISE:')                                  SPA02170
```

```
      WRITE(16,715)                                                    SPA02180
715   FORMAT(' ',6X,'MNVARX',13X,'MNVARY',13X,'MNVARZ')                SPA02190
      WRITE(16,713) MNVARX,MNVARY,MNVARZ                               SPA02200
C                                                                      SPA02210
510   CALL EXCMS ('CLRSCRN')                                           SPA02220
      WRITE (6,1008)                                                   SPA02230
      WRITE (6,*) '                                PROGRAM RUNNING'    SPA02240
C                                                                      SPA02250
C     ************       NOISE INPUT LOCATION        **************    SPA02260
C                                                                      SPA02270
      ROWN3 = NODE*6                                                   SPA02280
      ROWN2 = (NODE*6) - 1                                             SPA02290
      ROWN1 = (NODE*6) - 2                                             SPA02300
      COUNT = 0                                                        SPA02310
C                                                                      SPA02320
C     ************       INITIALIZE MATRICIES       ******************  SPA02330
C                                                                      SPA02340
      DO 54 K = 1, 200                                                 SPA02350
          X(K) = 0.0                                                   SPA02360
54    CONTINUE                                                         SPA02370
C                                                                      SPA02380
      DO 60 I=1,3                                                      SPA02390
         DO 58 J=1,3                                                   SPA02400
         RMN(I,J)=0.0                                                  SPA02410
         QPN(I,J)=0.0                                                  SPA02420
58       CONTINUE                                                      SPA02430
60    CONTINUE                                                         SPA02440
C                                                                      SPA02450
      RMN(1,1)=MNVARX**2.0                                             SPA02460
      RMN(2,2)=MNVARY**2.0                                             SPA02470
      RMN(3,3)=MNVARZ**2.0                                             SPA02480
      QPN(1,1)=PNVARX**2.0                                             SPA02490
      QPN(2,2)=PNVARY**2.0                                             SPA02500
      QPN(3,3)=PNVARZ**2.0                                             SPA02510
C                                                                      SPA02520
C     ***************************************************************  SPA02530
C     ******              BEGIN MAIN PROGRAM                    ******  SPA02540
C     ***************************************************************  SPA02550
C                                                                      SPA02560
      CALL STMTRX(EMODE,SMODE,SAMPT,DAMP,PHI,GAMMA,A,B,LAMA,UGVEX,C,   SPA02570
     +   ROWN1,ROWN2,ROWN3,BN)                                         SPA02580
C                                                                      SPA02590
C                                                                      SPA02600
      WRITE (6,1008)                                                   SPA02610
      WRITE(6,*) ' EXIT STMTRX - - - PRE-LOOP KALMAN'                  SPA02620
C                                                                      SPA02630
C                                                                      SPA02640
      WRITE (6,*) 'COMPUTING C TIMES SF FOR NEW C'                     SPA02650
C                                                                      SPA02660
      WRITE (16,1008)                                                  SPA02670
      DO 11000 I=1,200                                                 SPA02680
         DO 10900 J=1,NO                                               SPA02690
         C(J,I)= C( J,I)*SF                                            SPA02700
10900    CONTINUE                                                      SPA02710
11000 CONTINUE                                                         SPA02720
C                                                                      SPA02730
```

```
C     *** PRE-LOOP PORTION OF KALMAN FILTER                                SPA02740
C                                                                          SPA02750
C                                                                          SPA02760
      JK=SMODE*2-2                                                         SPA02770
      M2=2*MODE                                                            SPA02780
C                                                                          SPA02790
C                                                                          SPA02800
C     ************************************                                 SPA02810
C                                                                          SPA02820
      M2=2*MODE                                                            SPA02830
      JP=2*SMODE-1                                                         SPA02840
      JQ=2*EMODE                                                           SPA02850
C                                                                          SPA02860
C                                                                          SPA02870
      DO 8813 I=1,3                                                        SPA02880
      EX(I)=0.0                                                            SPA02890
8813  CONTINUE                                                             SPA02900
C                                                                          SPA02910
C                                                                          SPA02920
C                                                                          SPA02930
C                                                                          SPA02940
C     ************************************************************************SPA02950
C     ******     THIS SECTION COMPUTES THE STATE UPDATE     ******         SPA02960
C     ************************************************************************SPA02970
      ESS =0.0                                                             SPA02980
      COUNT = 0                                                            SPA02990
      ENERGY = 0.0D0                                                       SPA03000
      TIME = 0.0                                                           SPA03010
      CGN=0.0                                                              SPA03020
      CTG=0.0                                                              SPA03030
C     ******  SETS LOOP FOR THE ITERATIONS NECESSARY TO OBSERVE  ******    SPA03040
C     ******  THE SYSTEM FOR THE NUMBER OF MINUTES SPECIFIED     ******    SPA03050
      WRITE (6,1008)                                                       SPA03060
      WRITE (6,*) '            START STATE UPDATE     '                    SPA03070
      LOOP = INT((MIN*60.0)/SAMPT)                                         SPA03080
      PRT= (DBLE(LOOP))/30.0                                               SPA03090
      PRT1=(DBLE(LOOP))/50.00                                              SPA03100
      CTT=0.0                                                              SPA03110
C                                                                          SPA03120
      DO 400 L  = 0, LOOP                                                  SPA03130
         TIME = DBLE(L)*SAMPT                                              SPA03140
C                                                                          SPA03150
         IF(L.EQ.0)THEN                                                    SPA03160
            IMPLSE =(1.0D06*SF1)/(DSQRT(SAMPT))                            SPA03170
         ELSE                                                              SPA03180
            IMPLSE = 0.0D0                                                 SPA03190
         ENDIF                                                             SPA03200
C                                                                          SPA03210
      TO=0.0                                                               SPA03220
C     ****** RANDOM NUMBER GENERATOR *****                                 SPA03230
C                                                                          SPA03240
      DO 101 I=1,6                                                         SPA03250
      ISEED=MOD(ISEED*JR+KR,MR)                                            SPA03260
      RND1=(DBLE(ISEED)+0.5D00)/DBLE(MR)                                   SPA03270
      ISEED=MOD(ISEED*JR+KR,MR)                                            SPA03280
      RND2=(DBLE(ISEED)+0.5D00)/DBLE(MR)                                   SPA03290
```

```
      RNDM(I)=DSQRT(-2.0*DLOG(RND1))*DCOS(6.2831853D00*RND2)          SPA03300
101   CONTINUE                                                        SPA03310
C     **********************                                          SPA03320
      CTT=CTT+1.0                                                     SPA03330
C     ***** START OF STATE UPDATE ***                                 SPA03340
C                                                                     SPA03350
C     *** COMPUTE AX°200  = A°200 X 200  * X°200                      SPA03360
C                                                                     SPA03370
C                                                                     SPA03380
C     *** COMPUTE AXH = A*XH                                          SPA03390
C                                                                     SPA03400
      JK=SMODE*2-2                                                    SPA03410
      JP=JK+1                                                         SPA03420
      JQ=2*EMODE                                                      SPA03430
C                                                                     SPA03440
C                                                                     SPA03450
      DO 5015 I=NS,NF                                                 SPA03460
         SUM=0.0                                                      SPA03470
              DO 5010 K=NS,NF                                         SPA03480
              SUM=SUM+A(I,K)*X(K)                                     SPA03490
5010          CONTINUE                                                SPA03500
         AX(I)=SUM                                                    SPA03510
5015  CONTINUE                                                        SPA03520
C                                                                     SPA03530
C                                                                     SPA03540
C     *** COMPUTE WD°3                                                SPA03550
C                                                                     SPA03560
      WD(1)=PNVARX*RNDM(1)*TO+IMPLSE                                  SPA03570
      WD(2)=PNVARY*RNDM(2)*TO                                         SPA03580
      WD(3)=PNVARZ*RNDM(3)*TO                                         SPA03590
C                                                                     SPA03600
C     *** COMPUTE BNWD°200 =BN°200 X 3  * WD°3                        SPA03610
C                                                                     SPA03620
      DO 5035 I=NS,NF                                                 SPA03630
         SUM=0.0                                                      SPA03640
              DO 5030 K=1,3                                           SPA03650
              SUM=SUM+BN(I,K)*WD(K)                                   SPA03660
5030          CONTINUE                                                SPA03670
         BNWD(I)=SUM                                                  SPA03680
5035  CONTINUE                                                        SPA03690
C                                                                     SPA03700
C     *** COMPUTE X°200 =AX°200  + BNWD°200                           SPA03710
C                                                                     SPA03720
      DO 5040 I=NS,NF                                                 SPA03730
         X(I)= AX(I) + BNWD(I)                                        SPA03740
         IF (DABS(X(I)).LT. 1.0D-60) THEN                             SPA03750
              X(I)=1.0D-60                                            SPA03760
         END IF                                                       SPA03770
C                                                                     SPA03780
5040  CONTINUE                                                        SPA03790
C                                                                     SPA03800
C                                                                     SPA03810
C     **********************                                          SPA03820
C                                                                     SPA03830
C     *** START OF KALMAN FILTER ***                                  SPA03840
C                                                                     SPA03850
```

```
      JK=SMODE*2-2                                                    SPA03860
      JP=JK+1                                                         SPA03870
      JQ=2*EMODE                                                      SPA03880
      M2=2*MODE                                                       SPA03890
C                                                                     SPA03900
      JL=JQ+1                                                         SPA03910
      DO 8888 I=1,NO                                                  SPA03920
      SUM=0.0                                                         SPA03930
         DO 8887 K=JL,NF                                              SPA03940
         SUM=SUM+C(I,K)*X(K)                                          SPA03950
8887     CONTINUE                                                     SPA03960
      EX(I)=SUM*SUM*SAMPT+EX(I)                                       SPA03970
8888  CONTINUE                                                        SPA03980
C                                                                     SPA03990
C                                                                     SPA04000
      CGN=CGN+1.0                                                     SPA04010
      IF (CTT.EQ.1.0.OR.CGN.GT.PRT) THEN                              SPA04020
C                                                                     SPA04030
      WRITE (16,1008)                                                 SPA04040
      WRITE (16,*)   'TIME = ', TIME                                  SPA04050
C                                                                     SPA04060
      DO 380 I=JP , JQ                                                SPA04070
      WRITE (16,4500) I,X(I)                                          SPA04080
380   CONTINUE                                                        SPA04090
4500  FORMAT (' ',2X,'X(',I4,')= ',D15.8)                             SPA04100
C                                                                     SPA04110
      CGN=0.0                                                         SPA04120
      END IF                                                          SPA04130
C                                                                     SPA04140
C                                                                     SPA04150
400   CONTINUE                                                        SPA04160
      WRITE (11,*) 'SMODE = ', SMODE                                  SPA04170
      WRITE (11,*) 'EMODE = ', EMODE                                  SPA04180
      WRITE (11,*) 'SN = ',SN                                         SPA04190
      WRITE (11,*) 'FN = ',FN                                         SPA04200
                                                                      SPA04210
C                                                                     SPA04220
      JL=JQ+1                                                         SPA04230
      DO 9499 I=1,NO                                                  SPA04240
      WRITE (11,*) 'EX  ',I ,'     ', EX(I)                           SPA04250
9499  CONTINUE                                                        SPA04260
C                                                                     SPA04270
C                                                                     SPA04280
C                                                                     SPA04290
C                                                                     SPA04300
C                                                                     SPA04310
      CALL EXCMS ('CLRSCRN')                                          SPA04320
      WRITE (6,1008)                                                  SPA04330
C                                                                     SPA04340
599   STOP                                                            SPA04350
      END                                                             SPA04360
C                                                                     SPA04370
C                                                                     SPA04380
C                                                                     SPA04390
C                                                                     SPA04400
C                                                                     SPA04410
```

```
C     ************************************************************************      SPA04420
C     THIS SUBROUTINE COMPUTES THE STATE TRANSITION MATRIX FOR EACH                 SPA04430
C     OF THE 100 MODES                                                              SPA04440
C     ************************************************************************      SPA04450
C                                                                                   SPA04460
      SUBROUTINE STMTRX(EMODE,SMODE,T,D,PHI,GAMMA,A,B,LAMA,UGVEX,C,                 SPA04470
     +        ROWN1,ROWN2,ROWN3,BN)                                                 SPA04480
C                                                                                   SPA04490
      REAL*8 WN,GMA,PHI(2,2,100),GAMMA(2,100),EGT,T,COSW1T,SINW1T                   SPA04500
      REAL*8 W1,D,A(200,200),B(200,3),C(9,200),BN(200,3)                            SPA04510
      REAL LAMA(100),UGVEX(684,100)                                                 SPA04520
      INTEGER SMODE,R,EMODE,JJ,KK,ROWN1,ROWN2,ROWN3, NN(9), N9, NO                  SPA04530
C                                                                                   SPA04540
C                                                                                   SPA04550
      WRITE (6,*) 'INSIDE STMTRX - - COMPUTE WN, GMA, EFT, W1'                      SPA04560
C                                                                                   SPA04570
C                                                                                   SPA04580
      DO 600 I = 1    ,100                                                          SPA04590
         WN = DBLE(SQRT(LAMA(I)))                                                   SPA04600
         GMA = D*WN/2.0                                                             SPA04610
         EGT = DEXP(-GMA*T)                                                         SPA04620
         W1 = DSQRT((WN**2)-(GMA**2))                                               SPA04630
         COSW1T = DCOS(W1*T)                                                        SPA04640
         SINW1T = DSIN(W1*T)                                                        SPA04650
C                                                                                   SPA04660
C                                                                                   SPA04670
C                                                                                   SPA04680
C                                                                                   SPA04690
         IF(WN.EQ.0)THEN                                                            SPA04700
              PHI(1,1,I) = EGT*COSW1T                                               SPA04710
              PHI(1,2,I) = T                                                        SPA04720
              PHI(2,1,I) = 0                                                        SPA04730
              PHI(2,2,I) = EGT*COSW1T                                               SPA04740
C                                                                                   SPA04750
C                                                                                   SPA04760
C                                                                                   SPA04770
C                                                                                   SPA04780
C                                                                                   SPA04790
C                                                                                   SPA04800
              GAMMA(1,I) = 0                                                        SPA04810
              GAMMA(2,I) = 0                                                        SPA04820
         ELSE                                                                       SPA04830
C                                                                                   SPA04840
C                                                                                   SPA04850
C                                                                                   SPA04860
C                                                                                   SPA04870
         PHI(1,1,I) = EGT*(COSW1T + (GMA*(W1**(-1)))*SINW1T)                        SPA04880
         PHI(1,2,I) = (W1**(-1))*EGT*SINW1T                                         SPA04890
         PHI(2,1,I) = -(WN**2)*(W1**(-1))*EGT*SINW1T                                SPA04900
         PHI(2,2,I) = EGT*(COSW1T - (GMA*(W1**(-1)))*SINW1T)                        SPA04910
C                                                                                   SPA04920
C                                                                                   SPA04930
C                                                                                   SPA04940
C                                                                                   SPA04950
      GAMMA(1,I)=(WN**(-2))*(1.0D0-EGT*COSW1T -EGT*(GMA/W1)*SINW1T)                 SPA04960
```

```
         GAMMA(2,I) = (W1**(-1))*EGT*SINW1T                              SPA04970
C                                                                        SPA04980
C                                                                        SPA04990
C                                                                        SPA05000
C                                                                        SPA05010
         ENDIF                                                           SPA05020
C                                                                        SPA05030
C                                                                        SPA05040
C                                                                        SPA05050
600   CONTINUE                                                           SPA05060
C                                                                        SPA05070
      WRITE (6,*) 'PHI AND GAMMA COMPUTED'                               SPA05080
      WRITE (6,*) ' COMPUTING A, B, BN'                                  SPA05090
C                                                                        SPA05100
      R = 1                                                              SPA05110
C                                                                        SPA05120
      DO 610 K = 1    ,100                                               SPA05130
C                                                                        SPA05140
C                                                                        SPA05150
C                                                                        SPA05160
C                                                                        SPA05170
C                                                                        SPA05180
         A(R,R) = PHI(1,1,K)                                             SPA05190
         A(R,R+1) = PHI(1,2,K)                                           SPA05200
         A(R+1,R) = PHI(2,1,K)                                           SPA05210
         A(R+1,R+1) = PHI(2,2,K)                                         SPA05220
C                                                                        SPA05230
C                                                                        SPA05240
C                                                                        SPA05250
C                                                                        SPA05260
C                                                                        SPA05270
C     *** B MATRIX FOR MULTIPLYING CONTROL TORQUES                       SPA05280
C                                                                        SPA05290
         B(R,1) = GAMMA(1,K)*DBLE(UGVEX(412,K))                          SPA05300
         B(R,2) = GAMMA(1,K)*DBLE(UGVEX(413,K))                          SPA05310
         B(R,3) = GAMMA(1,K)*DBLE(UGVEX(414,K))                          SPA05320
         B(R+1,1) = GAMMA(2,K)*DBLE(UGVEX(412,K))                        SPA05330
         B(R+1,2) = GAMMA(2,K)*DBLE(UGVEX(413,K))                        SPA05340
         B(R+1,3) = GAMMA(2,K)*DBLE(UGVEX(414,K))                        SPA05350
C                                                                        SPA05360
C                                                                        SPA05370
C                                                                        SPA05380
C                                                                        SPA05390
C                                                                        SPA05400
C                                                                        SPA05410
C                                                                        SPA05420
C     *** BN MATRIX FOR MULTIPLYING THE NOISE DISTURBANCES               SPA05430
C                                                                        SPA05440
C                                                                        SPA05450
C                                                                        SPA05460
C                                                                        SPA05470
      BN(R,1)=GAMMA(1,K)*DBLE(UGVEX(ROWN1,K))                            SPA05480
      BN(R,2)=GAMMA(1,K)*DBLE(UGVEX(ROWN2,K))                            SPA05490
      BN(R,3)=GAMMA(1,K)*DBLE(UGVEX(ROWN3,K))                            SPA05500
      BN(R+1,1)=GAMMA(2,K)*DBLE(UGVEX(ROWN1,K))                          SPA05510
      BN(R+1,2)=GAMMA(2,K)*DBLE(UGVEX(ROWN2,K))                          SPA05520
```

```
      BN(R+1,3)=GAMMA(2,K)*DBLE(UGVEX(ROWN3,K))                          SPA05530
C                                                                        SPA05540
C                                                                        SPA05550
C                                                                        SPA05560
C                                                                        SPA05570
C                                                                        SPA05580
C                                                                        SPA05590
         R = R+2                                                         SPA05600
610   CONTINUE                                                           SPA05610
C                                                                        SPA05620
      WRITE (6,*) 'A, B, BN COMPUTED'                                    SPA05630
C                                                                        SPA05640
      WRITE (6,*) 'COMPUTING C'                                          SPA05650
C                                                                        SPA05660
C                                                                        SPA05670
C                                                                        SPA05680
C     *** C MATRIX PRODUCTION ***                                        SPA05690
      NO=3                                                               SPA05700
      NN(1)=418                                                          SPA05710
      NN(2)=419                                                          SPA05720
      NN(3)=420                                                          SPA05730
C                                                                        SPA05740
C                                                                        SPA05750
C                                                                        SPA05760
C                                                                        SPA05770
C                                                                        SPA05780
C                                                                        SPA05790
      JJ=-1                                                              SPA05800
      DO 640 I=1,100                                                     SPA05810
      JJ=JJ+1                                                            SPA05820
C                                                                        SPA05830
      DO 9127 K=1,NO                                                     SPA05840
C     .                                                                  SPA05850
      KK=I+JJ                                                            SPA05860
C                                                                        SPA05870
      N9=NN(K)                                                           SPA05880
C                                                                        SPA05890
      C(K,KK) = DBLE(UGVEX(N9,I))                                        SPA05900
C                                                                        SPA05910
      KK=KK+1                                                            SPA05920
C                                                                        SPA05930
      C(K,KK)=0.0                                                        SPA05940
9127  CONTINUE                                                           SPA05950
640   CONTINUE                                                           SPA05960
C                                                                        SPA05970
C                                                                        SPA05980
C                                                                        SPA05990
      RETURN                                                             SPA06000
      END                                                                SPA06010
```

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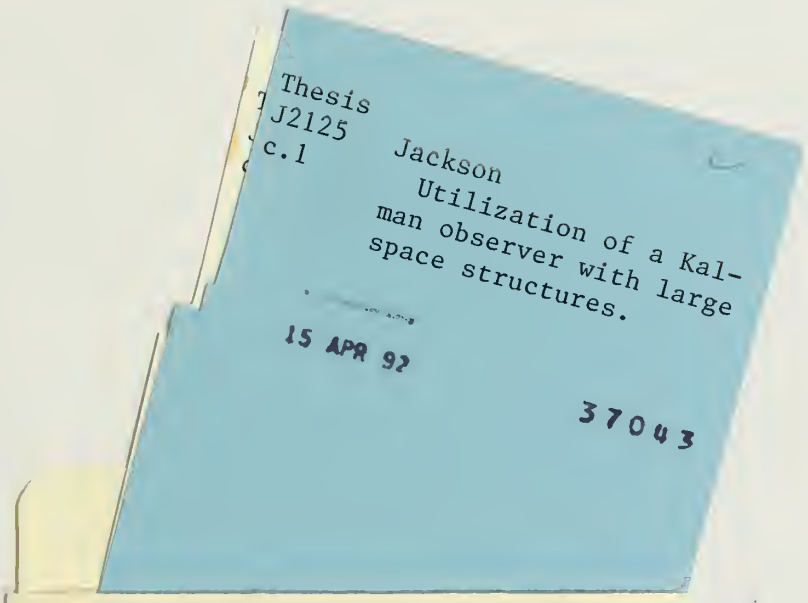
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